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Managing Vegetation to Increase Flow in the Colorado River Basin

Alden R. Hibbert

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General Technical Report RM-66
Rocky Mountain Forest and
Range Experiment Station
Forest Service
U. S. Department of Agriculture

Abstract

Water yield from forest and rangelands can be augmented by managing vegetation and snow to reduce evapotranspiration. Some arbitrary goals to increase water yield were chosen to illustrate the potential for increasing water yield, and treatments were hypothesized to get these increases.

General Technical Report RM-66, November 1979

Managing Vegetation to Increase Flow in the Colorado River Basin[1]

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[1]This report summarizes a much more detailed paper prepared in cooperation with the Pacific Southwest Interagency Committee. The main paper, "Vegetation management for water yield improvement in the Colorado River Basin," is available by accession number PB300379/AS from National Technical Information Service, U.S. Department of Commerce, 5825 Port Royal Road, Springfield, Va. 22161.

[2]Central headquarters at Fort Collins in cooperation with Colorado State University; author is at the Station's Research Work Unit at Tempe, in cooperation with Arizona State University.

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Management Implications

The combined surface and ground water supplies in the Colorado River Basin are generally adequate for current needs. However, growing demands and use of water in the Colorado River Basin could result in a widespread water shortage as early as 1995.[3] Local shortages exist already. One method of augmenting the water supply is management of forest and brush lands to increase streamflow.

Theoretically, the surface water supply in the Colorado River Basin could be increased by as much as one-third (6 million acre-feet annually) if vegetation and snow on 16% (26 million acres) of the basin were manipulated solely to increase water yield. However, other forest resources, economics, and social and environmental concerns must also be considered, which tend to greatly reduce both treatment area and effectiveness.

Water yield increases are greatest where large reductions can be made in water transpired by plants and/or evaporated from snow. Clearcutting and type conversion usually increase water yield the most. These practices may be appropriate in several vegetation types, such as chaparral and mountain brushlands, where the commercial value of the vegetation is low. However, where clearcuts and type conversions are not acceptable management practices, the potential for increasing water yield is less, although it may still be substantial in many cases.

Where much snow falls in windswept, treeless areas, evaporation of blowing snow can be reduced by trapping snow in large drifts behind snow fences, where it more effectively contributes to streamflow. Opportunities exist to increase water yield by this technique on selected sites in alpine, high elevation sagebrush, and mountain grassland areas. However, the high cost of snow fences and their visual impact on the open landscape must be taken into account.

In the examples used in this report, Upper Basin yield could be increased by 500,000 acre-feet per year, or 3.5%, by treating up to 22% of each vegetation type, except aspen, in which 40% would be treated. About one-half of the increase would come from the subalpine forests, including Douglas-fir. In the Lower Basin, more extensive treatments would be necessary to get an additional 250,000 acre-feet annually, an 8% increase in water yield. About 92% of the total increase would be generated by treatment of about 20% of the chaparral and 33% of the ponderosa pine.

While information on cost of producing extra water is incomplete, it is believed that the least expensive water would come from commercial forests, where timber yields would pay for part of the treatment costs. Water would be more expensive from type conversions, because most of the treatment costs would be levied against water production. However, most of the water is expected to cost less than imported water, and some of the water from commercial forests would supplement and be in the price range of water produced by weather modification.

[3] *U. S. Department of Interior, Bureau of Reclamation. Executive Summary of critical water problems facing the 11 western states. Westwide Study. 85 p.*

Introduction

Setting a realistic goal for increasing water yield through vegetation management requires a careful balance between needs, costs, and resource capabilities. The water user wants to know how much water can be produced and the cost. The land manager, however, must decide on resource allocations based on complex interactions with various segments of the public, and he must adhere to management guidelines stipulated by Congress.[4] Both the water user and the land manager need to consider how the cost of additional water production compares with the cost of achieving more efficient delivery and application of water already in the system. Further, the future demand for water and other forest resources and uses can change, and thus affect priorities and availability of treatable areas. Therefore, no attempt was made in this report to specify the amount of additional water that could be produced by management of vegetation and snow, except to show how arbitrary amounts might be generated by applying hypothetical treatments to selected portions of the Upper and Lower Basins. The examples chosen were not meant to suggest an attainable level of water yield increase, but rather to show the kinds of treatments and how much area might be affected, given an augmentation goal.

Public acceptance of water yield improvement practices will partly depend on how people view the need for more water (basically an economic issue), and on how they perceive the impacts of water improvement practices on the forest environment, including the less tangible resources such as wildlife and scenic beauty.

For water yield improvement projects to become fully effective would require several decades in commercial forests, where the rotation age of tree harvest may vary up to 120 years or more. Type conversion in brushlands would become operational much faster. Pilot applications help to bridge the gap between small watershed experimentation and large-scale action programs. An operational scale study of multiresource management in ponderosa pine is being conducted by the USDA Forest Service on the Beaver Creek Woods Canyon experimental watershed in central Arizona. A similar study is being initiated in the chaparral, and others are being considered for other vegetation types in both Upper and Lower Basins.

[4]Provisions of the Forest and Rangeland Resources Planning Act of 1974 (88 Stat. 476, et seq.), as amended by the National Forest Management Act of 1976 (90 Stat. 2949, et seq.) (16 U.S.C.1601-1614).

Water Resources in the Colorado River Basin

The Colorado River drains nearly 250,000 square miles, or 160 million acres in seven western states before entering the Gulf of California in Mexico. The basin includes virtually all of Arizona and portions of New Mexico, Colorado, Wyoming, Utah, Nevada, and California (fig. 1). The drainage area is divided into Upper and Lower Basins at Lee Ferry, about 10 miles south of the Utah-Arizona border. The Upper Basin contains about 70 million acres, and the Lower Basin contains 90 million acres. Lee Ferry is the official Compact point for apportioning flow from the Upper Basin for use by states within both the Upper and Lower Basins.

Precipitation averages 15.7 inches annually in the Upper Basin, where it concentrates in the mountains (fig. 1); the Lower Basin is drier, with 13 inches (fig. 1). The proportion of precipitation yielded as streamflow is more than five times greater in the Upper Basin (16% or 2.5 inches) than in the Lower Basin (3% or 0.4 inch). Overall, three-fourths of the water yield comes from less than 15% of the land area.

Precipitation and streamflow vary greatly from year to year. Annual yields from the Upper Basin at Lee Ferry have varied from 37% to 163% of the 83-year mean flow of 14.7 million acre-feet (fig. 2). Yield fluctuates even more in the Lower Basin. Seasonally, flow is concentrated in a few months out of each year when the snow melts.

Storage facilities are necessary to fully utilize water resources, especially additional water from vegetation management, because the increases are largest in wet years when flows already are high. Major reservoirs on the Colorado River and its tributaries provide usable storage for about 32 million acre-feet in each of the Upper and Lower Basins. When full, these reservoirs hold nearly four times the annual water yield of the entire Colorado River drainage area. In some headwater areas, however, seasonal deficiencies in water supply may develop because of inadequate storage facilities.

Water yield from the Upper Basin averaged 16.8 million acre-feet for the 26 years of records prior to the 1922 Colorado River Compact, which apportioned 7.5 million acre-feet for consumptive uses in the Upper Basin, and obligated the Upper Basin to release no less than 75 million acre-feet to the Lower Basin every 10 years (7.5 million acre-feet per year). A later commitment guaranteed delivery of 1.5 million acre-feet per year to Mexico, with the stipulation that both Upper and Lower Basins are to share equally in meeting this obligation if there

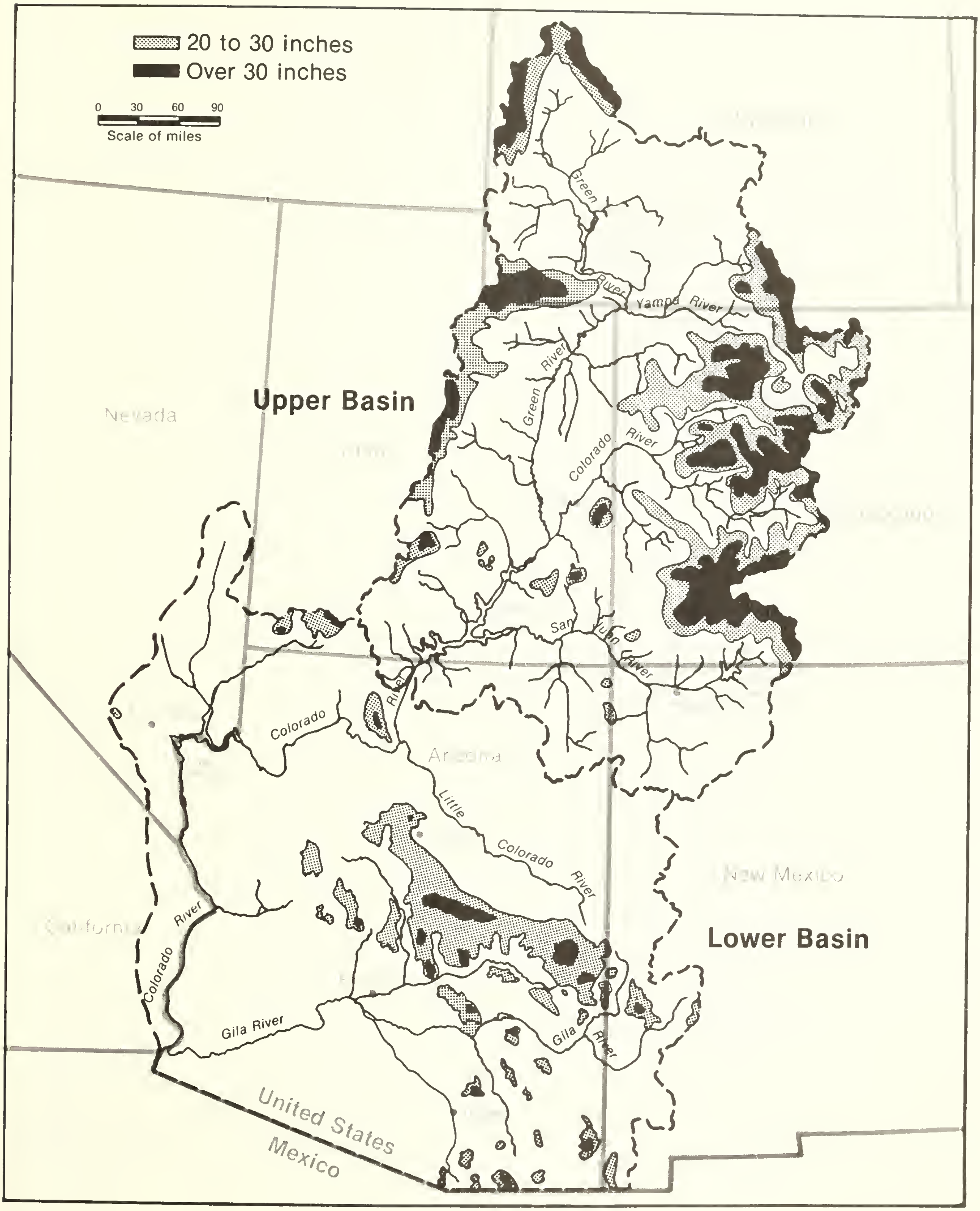

Figure 1.—Precipitation distribution is shown for the Upper and Lower Basins of the Colorado River which occupy portions of seven western states.

is insufficient water surplus to the apportionments. Together, these commitments totaled 16.5 million acre-feet, a not unrealistic demand on Upper Basin water yield based on records prior to 1922. Since then, however, undepleted flow at Lee Ferry has averaged less than 14 million acre-feet, which many believe is about all that can be expected over the long run. Long-term streamflow records, reconstructed from tree rings by Stockton and Jacoby (1976), indicate that for the past 450 years, flow at Lee Ferry has averaged 13.5 million acre-feet. Their analysis showed that only one other period, the early 1600's, was as wet as the first 30 years of this century.

While present mainstream water uses of about 12 million acre-feet per year in both Upper and Lower Basins are below the long-term trend in average annual water supply, this supply is less than the apportionments and the Mexican delivery obligation. Future water needs for development of the Basin's energy resources and other uses have been forecast to exceed supplies by about the year 2000.[5]

Water yield within Lower Basin watersheds is about 3.1 million acre-feet per year, much of which is used in Arizona. Additional large amounts of water are pumped from ground water to supply agriculture and municipal-industrial needs. Ground water overdraft in the Lower Basin averages nearly 2.5 million acre-feet per year. To sustain the current use rate will require continued overdraft of ground water, even with completion of the Central Arizona Project, unless the supply can be augmented.

[5] *USDI, Water for Energy Management Team. Report on water for energy in the Upper Colorado River Basin. 1974. 71 p.*

Increasing Water Yield by Management of Vegetation and Snow

Of the average 190 million acre-feet (14.2 inches) of rain and snow that fall each year on the Colorado River Basin, more than 90% of it evaporates. With such large amounts of water being returned to the atmosphere, even a slight reduction in this loss would leave substantially more water for streamflow. If, for example, evapotranspiration over the entire Colorado River Basin could be reduced by only 1%, the surface water supply would increase on the average by 1.75 million acre-feet annually. However, the opportunity to significantly reduce evapotranspiration by management of vegetation and snow is limited to certain types of cover. Only about 16% (26 million acres) of the basin is vegetated well enough or has sufficient snow to be suitable for water yield improvement measures.

Vegetation is controlled largely by climate. Areas of low rainfall dominate the Lower Basin, where vegetation is sparse and drought resistant. Precipitation generally increases with elevation and latitude, until at mid to upper elevations, brush, pinyon-juniper, and associated types are replaced by forests. Eventually, the forests give way to the cold, harsh climate of the alpine zone, where only low-growing forms of vegetation survive. Precipitation varies from less than 5 inches annually in the deserts to more than 50 inches in the wettest mountain areas. Potential evapotranspiration tends to be inversely related to precipitation, because energy for evaporation declines with increasing elevation, latitude, and cloudiness.

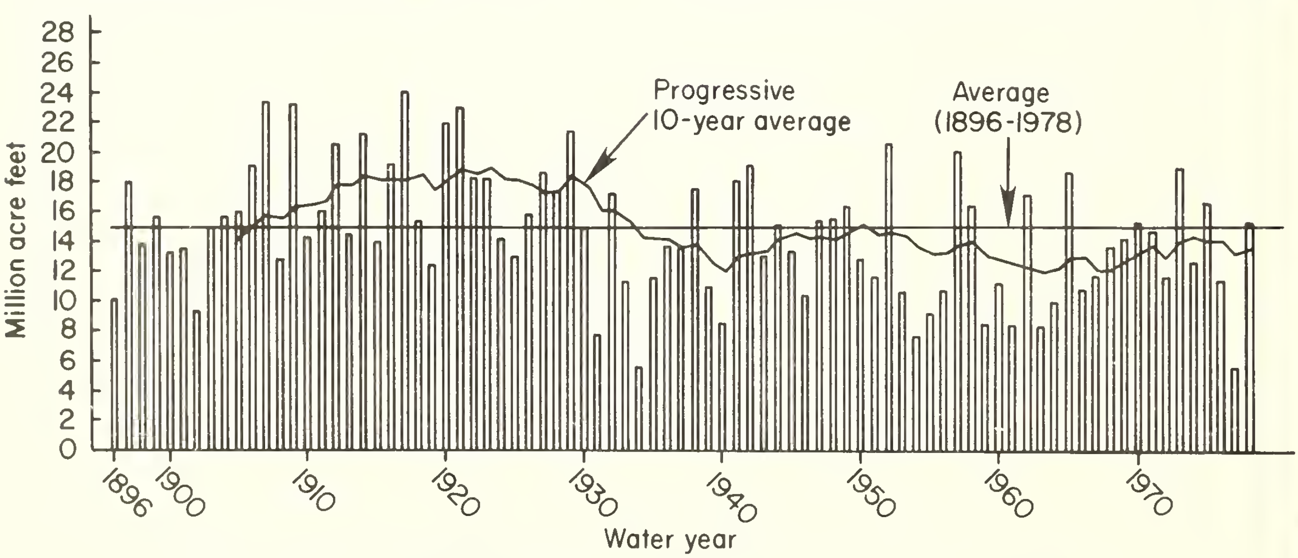

Figure 2.—Annual undepleted (virgin) flows of the Colorado River at Lee Ferry, Arizona, 1896-1978.

Water yield, therefore, increases rapidly with precipitation, from near zero in the deserts to as much as 40 inches in alpine areas.

Water yield improvement, as it pertains to forest and rangelands in the Colorado River Basin, is based on the premise that streamflow and/or ground water are increased by an amount equal to the net reduction in evapotranspiration. Little opportunity exists to reduce transpiration where precipitation is less than about 18 inches (fig. 3) and is exceeded by potential evapotranspiration (warm, dry portions in fig. 3), because rains do not penetrate far into the soil, and one cover type is about as efficient as another in using available water. At the other extreme (the cold, wet climate), the opportunity to decrease transpiration is limited because water use by plants already is low, and further reductions are difficult to obtain. The greatest opportunity exists where precipitation exceeds 18 inches and potential evapotranspiration (determined by the Thornthwaite method) exceeds 15 inches. This kind of climate promotes vigorous growth of vegetation capable of using large amounts of water. Modifying cover under these conditions can substantially increase water yield. Riparian vegetation represents a special situation because of water availability to plants in addition to natural precipitation in areas where the potential for evapotranspiration is often quite high.

The best opportunity to increase water yield by snow management is in cold climates where blowing snow can be concentrated in forest openings or trapped in large drifts to reduce evaporation.

Vegetation can be managed in several ways to reduce evapotranspiration:

1. Reduce stand density by various practices to reduce transpiration and interception.
2. Convert from one cover type to another that uses less water (type conversion).
3. Create openings in forest cover to reduce transpiration and to redistribute snow, concentrating it to reduce evaporation and increase snowmelt contribution to streamflow.
4. Establish trees or large shrubs in windswept, treeless areas to pile snow in large drifts, thereby reducing evaporation.

Snow management can save considerable water (Tabler 1973). As snow particles are blown along by wind in open terrain, they undergo significant evaporation (sublimation) loss and may completely sublimate after being transported a few thousand feet. By trapping snow behind natural or artificial barriers, such as snow fences, evaporation is reduced and snowmelt water is concentrated to enhance its delivery to the stream. In the forest, specific management practices can be used to promote redistribution of snow by wind from uncut areas of the forest to specially designed openings. When concentrated in this way, more of the snow melts and contributes to streamflow than if snow is uniformly distributed over the entire forested area.

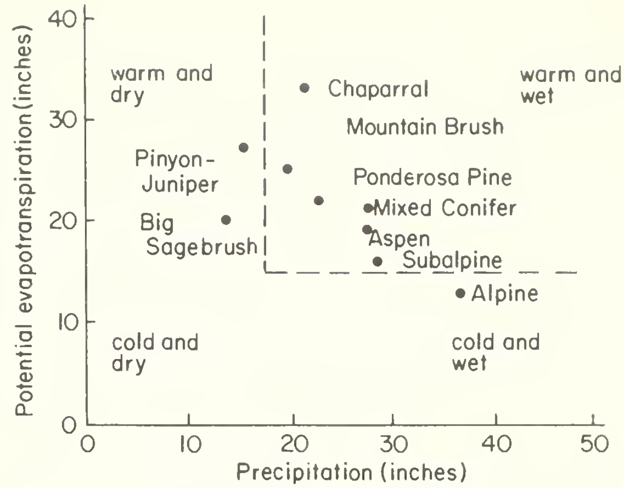

Figure 3.—General relationship of vegetation to potential evapotranspiration (PE) (Thornthwaite and Mather 1957) and precipitation (P) in the Colorado River Basin. The ranges in PE and P are broader than indicated by the average values plotted for each vegetation type. Aspen, for example, overlaps the area between ponderosa pine and subalpine. The dashed lines represent approximate marginal conditions for improving water yield by manipulation of vegetation; the potential is greater in the direction of warm and wet climate.

The method of treatment will vary with vegetation type, climate, soils, topography, and with social, economic, and environmental considerations. Clearcutting and type conversion usually produce maximum increases in water yield compared to thinning and patch cutting. An exception may be in areas of heavy snowfall, where patch cuts or strip cuts of appropriate size and spacing appear more efficient then large clearcuts (Leaf 1975).

Thinning, the uniform reduction of forest cover, is probably the least effective method of increasing water yield in the Colorado River Basin, where summer moisture usually falls short of plant water demands. As soil water depletes during the growing season, plants compete for available moisture. In this situation, plants that remain after thinning are capable of using additional water if it becomes available by removal of nearby plants (fig. 4). As a general rule, uniform thinning of forest and brush stands in the Rocky Mountains and Southwest must remove about 50% of the crown cover before water yield appreciably increases. For this reason, silvicultural systems that use shelterwood or indi-

vidual tree selection methods of harvest are not as water productive as harvest systems that create openings in the forest cover.

Type conversion, the permanent replacement of one cover type with another (fig. 5), may be appropriate in several vegetation types. In addition to water, other benefits, such as increased forage and reduced fire hazard, may accrue. However, other resources, such as timber, food and cover for wildlife, scenic values of the landscape, and soil stability, require consideration in resource management decisions. Such considerations will bear on how much of the water yield potential can actually be achieved.

Potential Increases by Vegetation Types

Eleven cover types were delineated based on differences in water response to treatment. These cover types are alpine, mountain grasslands, subalpine, mixed conifer, aspen, ponderosa pine, mountain brush, chaparral, big sagebrush, pinyon-juniper, and upstream riparian. Together these cover types occupy some 76 million acres in the Colorado River Basin, nearly one-half of the total area. However, about 50 million acres are classified as sagebrush and pinyon-juniper which have little or no potential, except on exceptional sites. Thus the focus is on about 26 million acres or 16% of the entire basin. Phreatophytes along downstream portions of the major rivers were not included in this study.

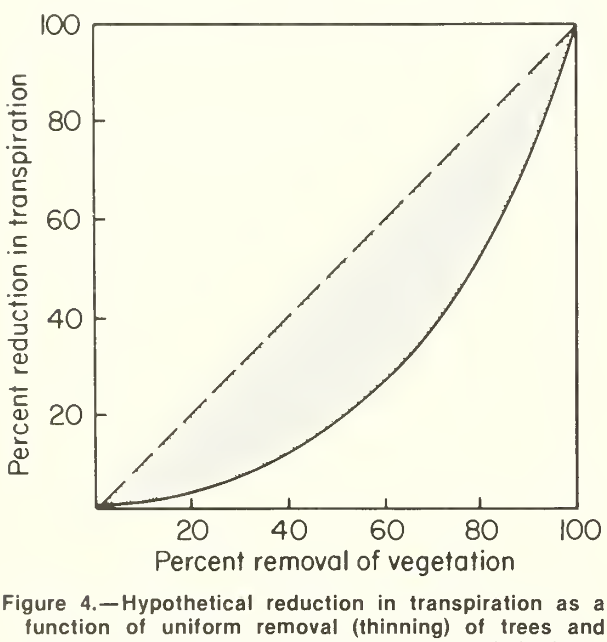

Figure 4.—Hypothetical reduction in transpiration as a function of uniform removal (thinning) of trees and shrubs under conditions that vary from unlimited soil water availability to plants (shaded portion trending toward broken line) to definitely limited availability (shaded portion trending toward solid line).

Figure 5.—Type conversion of brush to grass (foreground) increases water and forage yields, improves wildlife habitat by increasing edge and species diversity, and reduces fire hazard by breaking up large, continuous blocks of dense cover.

The potential for increasing water yield for each type was determined after thorough review of numerous research documents including 11 state-of-knowledge reports on watershed management recently published by the Rocky Mountain Forest and Range Experiment Station. To conserve space, reference to much of the source materials has been omitted in this report. However, a complete list of references is included in the main paper,[1] which provides greater detail on each vegetation type.

The increases are presented as the average maximum or near maximum onsite response to treatment, usually by clearcutting and type conversion. The increases for some vegetation types were then adjusted, where appropriate, to reflect the experience of some units in making adjustments for multiple use and other considerations. The increases are projected as long term averages that could be sustained indefinitely with maintenance programs. Except for the chaparral, there has been no reduction for any offsite transmission losses that might occur.

The Alpine Zone

The alpine zone is that part of the mountains above erect tree growth, which occurs at 10,000 to 12,000 feet elevation (fig. 6). Cover consists primarily of low-growing grasses, sedges, forbs, lichens, and dwarf willows. About 1.3 million

acres have been classified as alpine, virtually all of it in the Upper Basin. About 98% is National Forest land. The climate is cold, wet, and windy. Precipitation averages 40 inches or more annually, and comes mostly as snow, which is redistributed by the wind. Water yield averages 20 to 40 inches; 85% is concentrated in the May-July snowmelt period.

There is potential for increasing water yield on selected sites where evaporation of windblown snow can be reduced by trapping snow in large drifts (fig. 7). Where snow trapping is efficient, tests have shown that roughly 60 to 120 feet of fence is required to retain an extra acre-foot of water in the snow drift at the start of the melt season (Martinelli 1975). In terms of volume per unit length of fence, this amount is equivalent to 363 to 726 cubic feet per foot of fence or 44 to 88 acre-feet per mile of fence. If fences could be spaced at 500- to 1,000-foot intervals, for example, the extra water trapped would be equivalent to a uniform depth of about 4 to 17 inches over the area between fences. However, increases of this magnitude have not been demonstrated over large areas. In field application, spacing of fences could vary considerably depending on terrain, wind, and snow supply. If spacing should average 2,000 feet, the potential for increasing snow storage would be 2.2 to 4.4 inches. Even this amount should be considered tentative until results from additional research and pilot tests become available. In addition, most artificial structures are easily seen from long distances; therefore, the visual impact of such barriers should be taken into account.

Mountain Grasslands

High elevation mountain grasslands (fig. 8) and other large forest openings covered by grasses, forbs, and low-growing shrubs provide additional opportunity to increase water yield by snow management. These areas are below timberline; the reason they are treeless is not always clear. There

Figure 6.—The alpine zone in Colorado with transition to subalpine vegetation at right. The alpine zone occupies about 1.3 million acres in the Upper Basin and only about 2,000 acres in the Lower Basin.

Figure 7.—Natural drifting of snow (foreground) in the alpine can be enhanced by placing fences to put additional snow on top of an already deep snowpack. This is done to increase the runoff during summer months from such areas.

Figure 8.—High elevation (9,000-10,000 feet) mountain grasslands in eastern Arizona, where much sublimation loss occurs from windblown snow. These areas comprise about 100,000 acres in the Lower Basin and an unknown acreage in the Upper Basin.

are an estimated 100,000 acres in the Lower Basin. In the Upper Basin, these areas may be even more extensive, but the acreage is not known. In forest surveys, these areas are often included with associated noncommercial subalpine, aspen, and mixed conifer forests. Climate is similar to the associated types, although wind is usually stronger in the large openings. Precipitation averages 25 to 40 inches annually, and is mostly snow. Water yield may range from 3 inches to as much as 15 inches on the wettest sites.

The potential for increasing water yield is believed to be less than in the alpine zone because of less snow and wind. It has been estimated that streamflow from mountain grasslands in eastern Arizona could be increased by 1.5 to 2 inches if snow could be held in large drifts where it falls instead of being blown long distances across these areas (Thompson et al. 1976). Again, an important consideration is the visual impact of snow fences.

Rocky Mountain Subalpine Forests

Conifer forests, including spruce-fir, lodgepole pine, Douglas-fir, mixed conifers, and ponderosa pine, cover nearly 15 million acres within the Colorado River Basin, of which nearly 13 million acres are classified as commercial. Subalpine forests (fig. 9), composed of spruce-fir, lodgepole pine, and, for purposes of this report, Douglas-fir, occupy some 6.8 million acres in the Upper Basin; 5.5 million acres of these are considered commercial. The elevation of these forests varies from 7,000 to 11,500 feet, just below the alpine zone. The climate is cool and moist; mean temperature is near freezing. Precipitation is about two-thirds snow and averages from 20 to as much as 55 inches per year. Water yield may vary from 5 to as much as 40 inches per year, largely from snowmelt. Overall, the average precipitation is estimated at 28-30 inches and streamflow (water yield) at 12-15 inches (Leaf 1975).

The potential is good for increasing water yield in the subalpine type by managing for snow redistribution and transpiration reduction in small forest openings (Leaf 1975). Increases in water yield of from 1 to 3 inches (fig. 10) can be expected, depending on site factors and management strategies. Simulation harvest of lodgepole pine (fig. 10) was by a series of patch cuts, 5 to 8 tree heights in diameter, each covering about one-third of the planning unit. The cuts would be made at 30-year intervals spread over a planning period of 120 years with periodic thinning in the regenerated stands. The management strategy for the

Figure 9.—Subalpine forests cover approximately 6.8 million acres in the Upper Colorado River Basin. The spruce-fir type, shown in this watershed view in the Colorado Rockies, makes up about 50% of the total subalpine area.

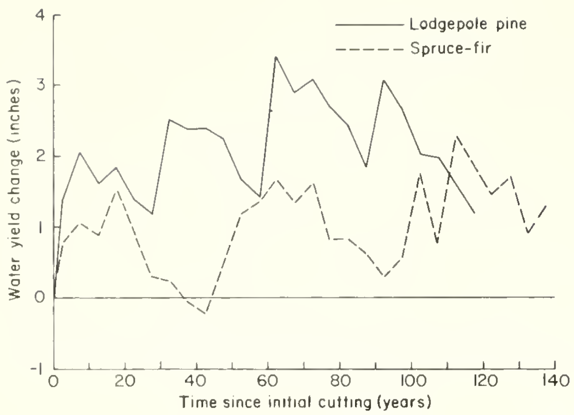

Figure 10.—Projected water yield increases from specific management strategies in lodgepole pine and spruce-fir forests (Leaf and Alexander 1975).

Figure 11.—Mixed conifer forests, including Douglas-fir in the Southwest occupy about 400,000 acres in the Lower Colorado River Basin.

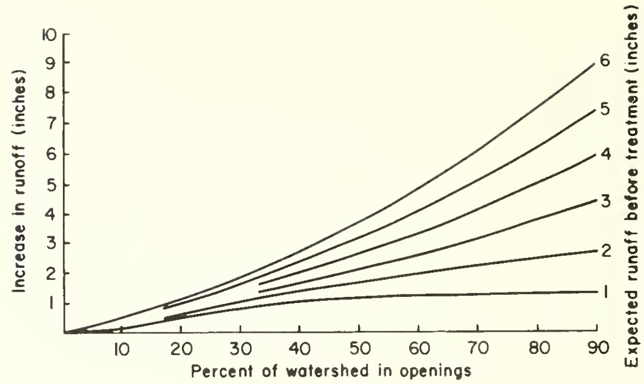

Figure 12.—Potential water yield increases from mixed conifer forests as a function of the percent of watershed in openings 3 to 8 tree heights in diameter and the expected yield without treatment (Rich and Thompson 1974).

spruce-fir (fig. 10) was similar, except that the patch cuts would be made at 50-year intervals. In much of the Rocky Mountain area, patch cutting is considered ecologically sound if the management objective is to maintain the spruce-fir ecosystem (Alexander 1974).

Southwestern Mixed Conifer Forests

Mixed conifer forests (fig. 11) in the Southwest occupy sites that are wetter and cooler than usually occupied by pure stands of ponderosa pine and warmer, but not necessarily drier, than subalpine forest sites to the north. The most common overstory species are Douglas-fir, ponderosa pine, white fir, Engelmann spruce, aspen, southwestern white pine, blue spruce, and corkbark fir. Most of the mixed conifer stands are found between 7,000 and 10,000 feet elevation. Above 10,000 feet, mixed conifers give way to spruce-fir forests. Douglas-fir is the most important commercial timber species. For purposes of this report, all spruce-fir in the Lower Basin is included in the mixed conifer type. Together they occupy nearly 400,000 acres, mostly commercial. Precipitation averages 25 to more than 30 inches per year; one-half or more of it comes as snow. Water yield averages 3 to 5 inches, sometimes more on the wettest sites; three-fourths or more of it is from snowmelt.

Using management strategies similar to those described for subalpine forests, the potential for increasing water yield in the mixed conifer forests is estimated to be about 25% less than in the subalpine, although large clearcuts appear to give greater increases in the mixed conifer than in the subalpine. A possible explanation for this is that in

the drier, warmer climate of the mixed conifer forests, more of the response from altering the cover is attributed to reduction in transpiration and less to redistribution of snow. Increases in water yield of 3 to 4 inches are possible from clearcutting (Rich and Thompson 1974). However, without type conversion to an herbaceous cover, the increases would decline as the forest regrows. The overall estimate is 1.5 inches average increase from maintaining about one-third of the area in small openings on sites where streamflow normally averages 4 to 5 inches (fig. 12).

Rocky Mountain Aspen Forests

Quaking aspen (fig. 13) occupies approximately 3.3 million acres in the Colorado River Basin, nearly all of it in the Colorado and Utah portions of the Upper Basin. Roughly 75% is on National Forest land. The aspen type is recognized for its multiple values of wood, livestock forage, wildlife habitat, watershed protection, recreation, and esthetics. Aspen is commonly found between 7,000 and 10,000 feet elevation in clumps to extensive stands interspersed among conifers of the subalpine, mixed conifer, and cooler portions of the ponderosa pine type. Precipitation averages 20 to 40 inches, one-half or more of it snow. Water yield averages 3 to 5 inches in the Lower Basin, but may reach 20 inches in the Upper Basin.

The potential is good for increasing water yield in the aspen by type conversion, but relatively low from cutting or other practices when the objective is aspen stand regeneration. Increases up to 5 inches are possible from clearcutting aspen (DeByle 1976), but these increases decline rapidly and are gone within 10 to 15 years (fig. 14), if this prolifically sprouting species is allowed to recover the site. Therefore, if clearcutting or other removal practices were to be repeated every 80 years, as might be done for timber harvest with stand regeneration, the average annual increase over 80 years would be about one-third inch over the area actually treated. More frequent treatment has been suggested to enhance browse production for deer and elk and domestic animals (Patton and Jones 1977). If clearcutting or other methods of stand removal were practiced on a 25-year rotation, for example, increases averaging about 1 inch per year would be possible on the area actually treated.

Southwestern Ponderosa Pine Forests

Ponderosa pine (fig. 15) occupies about 1.5 million acres in the Upper Basin and about 6 million acres in the Lower Basin. About 70% is on

Figure 13.—Quaking aspen is widespread in the Colorado River Basin, with more than 90% of the 3.3 million acres located in western Colorado and eastern Utah.

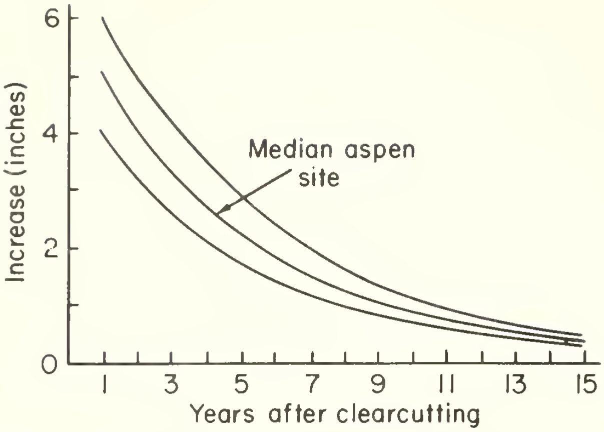

Figure 14.—Increase in water yield declines rapidly after clearcutting aspen, when regrowth is permitted (personal communication with Norbert V. DeByle, Intermountain Forest and Range Experiment Station, Forestry Sciences Laboratory, Logan, Utah).

public lands, with most of the remainder on Indian lands. Of the nearly 6.9 million acres considered capable of commercial timber production, nearly two-thirds of a million acres are in National Parks, wilderness areas, high value scenic areas, and similar land use categories. The elevation range for ponderosa pine is between 6,000 and 9,000 feet, where the type grows best on sites that are warmer and drier than those occupied by mixed conifer and subalpine forests. Gambel oak and chaparral species are common understory plants in the lower fringe area of the pine. Annual precipitation is about one-half snow and averages from 15 to 25 inches in the Upper Basin and 20 to 25 inches in the Lower Basin. Water yield is derived mostly from snowmelt and averages 2 to 6 inches annually, depending on precipitation, elevation, and soils. The overall average is probably 3 to 4 inches.

The potential for increasing water yield in ponderosa pine is less than from other commercial

Figure 15.—Ponderosa pine near Flagstaff, Ariz. after an improvement selection cut in 1941. Note thick reproduction at left. There are approximately 1.5 million acres of ponderosa pine in the Upper Basin and 6 million acres in the Lower Basin.

forest types, presumably because the pine forests are drier. Short-term increases of 1 to 3 inches may be expected from clearcutting ponderosa pine with basal area in excess of 100 square feet per acre, although these increases would not continue indefinitely without maintenance of the clearcut condition. Under a multiple use management framework, in which timber, range, wildlife, recreation, and water would all be considered in the product mix, the long-term increases of 0.1 to 1 inch are more realistic expectations (H. Brown et al. 1974). The actual amount depends on the forest cover present before treatment and the amount and method of forest reduction (fig. 16). The average increase is probably about one-half inch, unless special emphasis is placed on water production. Under a water-emphasis plan, about 1 inch might be expected where substantial reductions can be made in the forest cover by patch or strip cuts or severe thinning to a stocking level of about 40 square feet basal area per acre. Current low to intermediate stocking levels on approximately two-thirds of the ponderosa pine (Schubert 1974) (fig. 17) may preclude water increases from these areas regardless of the management emphasis, except for clearcutting.

Chaparral

The chaparral type (fig. 18) is restricted almost entirely to the Lower Basin, where it covers approximately 3.5 million acres, nearly all in Arizona. About one-half is in the National Forest system; the remainder is nearly equally divided between the Bureau of Land Management, the State of Arizona, and private and Indian ownership. Unlike the mountain brush in Colorado and Utah, the chaparral species tend to be low-growing shrubs with thick, evergreen leaves well adapted to heat and drought. The type is found most commonly on rugged terrain from 3,000 to 6,000 feet elevation. Shrub live oak is most abundant, followed by mountainmahogany. Other common shrubs are manzanita, Emory oak, silktassel, desert ceanothus, and sugar sumac.

Most species sprout prolifically from root crowns after burning or cutting; most are difficult to eradicate. Precipitation averages 20 to 22 inches overall, but ranges from as low as 16 inches in the lower fringe areas to more than 25 inches in the wettest sites. Half or more of the precipitation falls in the winter, mostly as rain. Water yield varies greatly depending on precipitation, elevation, and

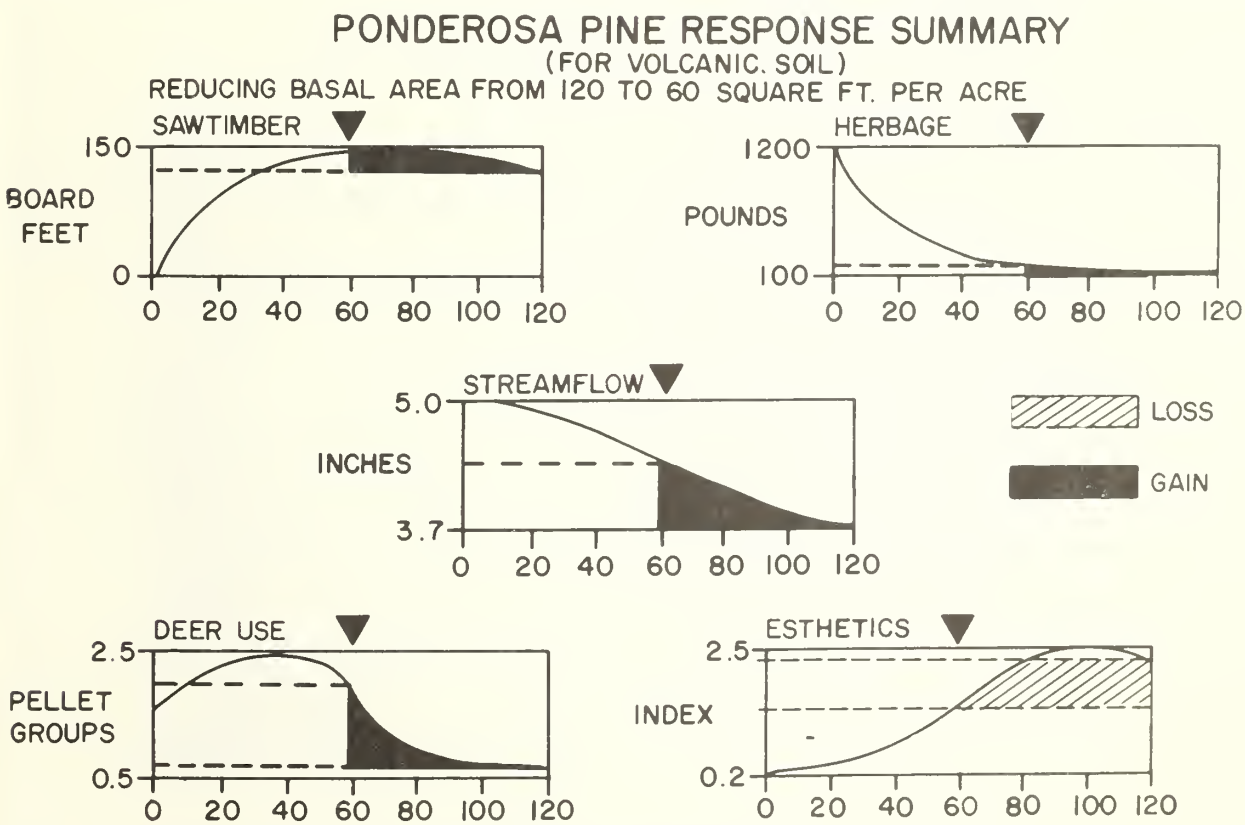

Figure 16.—Differences in resource outputs resulting from changes in timber basal area in ponderosa pine (Baker and Brown 1974).

Figure 17.—Fire has virtually eliminated ponderosa pine on this area. There are thousands of acres like this in the Southwest, that, if reforested, would likely result in less water yield than is now being produced.

Figure 18.—Chaparral covers about 3.5 million acres in the Lower Basin. This view is of 3 Bar Experimental area in central Arizona 8 years after wildfire in 1959 topkilled the dense stand of brush. The 96-acre watershed at left center was converted to grass.

soils. The overall average is 1 inch or slightly more; the lower, drier sites produce very little, while the wettest sites may yield 3 or 4 inches.

The potential for increasing streamflow by type conversion of chaparral is good on favorable sites where precipitation averages 20 inches or more (Hibbert et al. 1974). The key to increasing water yield is the replacement of deep-rooted shrubs with shallow-rooted grasses and forbs that use less water. The onsite increases determined from experimental type conversions on small watersheds range from less than 1 inch to more than 5 inches (fig. 19). The average is 3.8 inches at 22 inches precipitation. Some discounting is in order before extrapolating the research results to larger areas where conversion may not be as intensive, continuous, or as well maintained as on the experimental watersheds. Moreover, some of the increased flow may be lost to riparian vegetation downstream before it reaches storage or points of use. Therefore, the average increase expected downstream from type conversion is estimated to be about two-thirds of the onsite increase, or 2.4 inches where precipitation is 22 inches (considered average for treatable chaparral). Other considerations will limit the amount of type conversion to a fraction of the total acreage.

Of the 1.8 million acres of chaparral on National Forest lands, more than 200,000 acres are in wilderness and other special use areas, where conversion is not compatible with present land use policy. A much larger portion, nearly 40% of the remaining chaparral, is considered too dry and open (crown cover less than 30%) to be a good risk for water yield improvement. Also, much of the chaparral is on excessively steep slopes. In a study of chaparral conversion potential on National Forest lands in the Salt-Verde Basin above Phoenix, Ariz. (T. Brown et al. 1974), about 10% of otherwise treatable chaparral was on slopes steeper than 60%, which was the upper limit considered safe for conversion. However, some land managers feel that the 60% slope criterion is too steep for practical field application, and that the upper limit should be 50%, or even 40%. Since approximately 40% of the chaparral is on slopes between 40% and 60%, the steepness at which conversion can be safely accomplished is extremely important. Approximately 20% less area would be available for conversion if the maximum operable slope is lowered from 60% to 50%, and another 20% of acreage would be lost between 50% and 40% slope. Also, substantial acreages may be excluded for treatment, or given low priority, because of operational restrictions or geographic location, such as chaparral on slopes of isolated mountain ranges, where an increase in water would be of questionable value. Therefore, both the 1 acre in 5 estimate for treatable chaparral and the 2.4-inch water yield increase projection probably would be considered the most optimistic potentials attainable by large-scale management efforts in the chaparral.

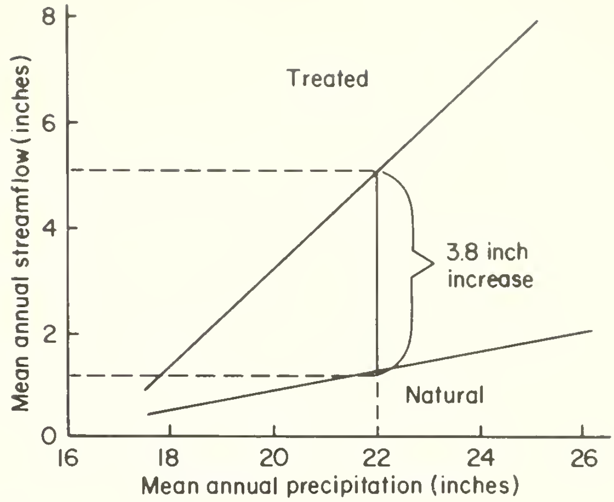

Figure 19.—Average water yield from natural and converted chaparral is a function of precipitation. Difference between lines is attributed to treatment (Hibbert et al. 1975).

Further, use of the arithmetic average to describe annual water yield potential can be misleading, because this value (2.4 inches in this case) will not be equalled or exceeded 50% of the years as would occur if precipitation and runoff were normally distributed. In the chaparral of central Arizona, precipitation is less than average about 58% of the years. Since runoff increases exponentially with precipitation, yearly runoff amounts are skewed ever farther to the dry side of the distribution curve. Wet years tend to yield many times as much water as dry ones. Thus, even though precipitation exceeds the mean in only about 4 years in 10, more than 80% of the water yield increases are produced in these wetter than average years. Storage facilities are imperative to get full benefit of increased water yields in wet years. To the extent that downstream storage capacity is exceeded (which happened 7 times in the past 50 years in the Salt-Verde Basin above Phoenix) and water is spilled, runoff increases from conversion would be lost to the full extent of the release, assuming no further beneficial use could be made of the water downstream.

Mountain Brush

Mountain brushlands (fig. 20) are extensive only in the Upper Basin, where they are found on about

3.3 million acres. Less than one-third of the area is under National Forest administration. The Bureau of Land Management administers much of the remainder, with undetermined acreages in state, private, and Indian ownership. Gambel oak, mostly in brush form, growing 2 to 12 feet high in clumps or thickets, is the predominant species. Associated shrubs, which sometimes dominate the site, are chokecherry, serviceberry, snowberry, big sagebrush, mountainmahogany, and other woody species. Though sometimes classified as chaparral, and similar in appearance, the mountain brush type differs in that most of the species are deciduous; thus they are active only in the summer. The type is commonly found at 5,000 to 10,000 feet elevation on relatively warm, dry exposures. Average annual precipitation ranges from 16 to 24 inches, less than one-half falling as snow. Water yield of 1 to 6 inches can be expected.

There has not been sufficient research in the mountain brush to accurately predict how treatment will affect water yield. However, results from plot studies in Utah (Johnston et al. 1969) suggest that response to brush conversion may be less than in the chaparral. A rough estimate is 1 to 3 inches of additional water from type conversion. If shrub regrowth is not controlled, the increase will be short-lived, probably about 3 to 5 years. It is difficult to estimate the amount of mountain brush that would or could eventually be converted to grass, in view of other resource values and social and economic factors that should be considered in resource management decisions.

Big Sagebrush

Big sagebrush (fig. 21) is found on some 26 million acres in the Colorado River drainage area, mostly on lands administered by the Bureau of Land Management. Only a small percentage of the 18 million acres in the Upper Basin, and none in the Lower Basin are considered as having potential for increasing water yield. Big sagebrush thrives over a broad range in elevation and climate. It is found at elevations up to 10,000 feet, and is well adapted to warm, dry growing seasons at lower elevations. Precipitation varies from 8 to 20 inches; only the wettest sites have potential for water yield improvement by vegetation manipulation. Water yield is less than 1 inch on most sagebrush lands. However, where precipitation exceeds 14 inches, yield may be greater; it can reach 3 to 4 inches on the wettest sites. The relocation of snow by winter winds and the resulting water loss by sublimation are important features of this type.

The potential for increasing water yield in big sagebrush is poorly defined, although type conversion on the most favorable sites might increase yield by 15%, or up to one-half inch (Sturges 1975).

Figure 20.—Mountain brush (mostly Gambel oak, as in this photo) covers some 3.3 million acres of mountain lands in the Upper Basin.

Figure 21.—Big sagebrush covers vast areas in the Upper Basin. However, there is potential for increasing water yield only on the most favorable sites by management of the vegetation and snow.

Figure 22.—By trapping snow behind snow fences such as this evaporation of blowing snow is reduced, and snowmelt water is concentrated to enhance its delivery to the stream or ground water recharge.

Additional increases of 1 inch or more may be possible by trapping blowing snow behind snow fences (fig. 22) in areas where the winter snow water equivalent is at least 8 inches (Tabler 1975).

Pinyon-Juniper

The pinyon-juniper ecosystem is the most extensive forest type in the Colorado River Basin, occupying some 32 million acres. Pinyon-juniper lands are mostly under federal administration: roughly 32% Bureau of Land Management, 20% USDA Forest Service, 19% Indian trust, and 29% other, including state and private holdings. Principal species are Utah, Rocky Mountain, one-seed, and alligator junipers, and Colorado and single leaf pinyon pines. The type is most commonly encountered in the foothills, low mountains, and low plateaus between 4,000 and 7,500 feet elevation. Though normally considered low in commercial value, the pinyon-juniper type has been and still is an important source of forage for livestock, food and cover for wildlife, and various products such as fence posts, firewood, pinyon nuts, and Christmas trees. Extensive pinyon-juniper control programs have been conducted in the Southwest (fig. 23).

Precipitation averages 12 to 18 inches, with local areas receiving up to 20 inches. Summer rains account for half or more of the precipitation in the Lower Basin, while winter rains and snow provide the bulk of the moisture in the Upper Basin. Water yield is generally less than 1 inch, although some of the better watered sites may approach 3 inches.

The potential for increasing water yield in the pinyon-juniper type is negligible on most sites, although small increases (less than 0.5 inch) may be possible by type conversion on the wettest sites (Clary et al. 1974). Overall, the potential should be considered poor.

Upstream Riparian Areas

Upstream riparian areas (fig. 24) consist of riparian vegetation along relatively small streams that drain to the Colorado River and its major

Figure 23.—Pinyon-juniper conversion remains controversial (Lanner 1977); however, when treated areas are kept small and fitted to the natural landscape, the visual impact is greatly reduced, wildlife habitat is improved, and forage production is increased (Hurst 1976). Water yield is little affected by conversion.

tributaries. Of particular interest are streams that emerge from the mountains and flow across hot, dry lowlands to reach major streams and reservoirs. Total area occupied by these bands of vegetation exceeds 100,000 acres, the estimate for the Lower Basin alone. No acreage figure is available for the Upper Basin. Common riparian trees and shrubs are cottonwood, willows, saltcedar, arrowweed, saltbushes, mesquite, sycamore, and alders. Elevations range from about 1,000 feet to over 7,500 feet. Estimates of potential evapotranspiration for the lowest elevations are as high as 6 feet per year. The upstream riparian areas are of special interest because they are (1) areas of heavy water consumption, (2) conveyance systems for water yield increases generated on upstream watersheds, (3) areas of high potential for saving water by eradication of trees and shrubs, and (4) areas of high scenic value and high value for wildlife and recreation.

The potential for increasing water yield in the upstream riparian areas can be greater per unit area than for any other vegetation type. Water savings of from 6 to 24 inches appear possible when riparian vegetation is eradicated along permanently flowing streams (Horton and Campbell 1974). However, extensive removal of trees and shrubs from these areas could impair scenic and recreation values, adversely affect channel stability, and destroy some of the most productive wildlife habitat in the Southwest. Less than complete removal of trees and shrubs would correspondingly reduce the water savings potential. Thus it appears unlikely that upstream riparian areas can be counted on for significant augmentation of the water supply.

Summary of Potential Increases and Comparison with Earlier Estimates

The potentials for increasing water yield in 11 cover types are summarized in tables 1 and 2 for the Upper and Lower Basins. The data are presented as ranges of average onsite increases in area inches

Figure 24.—Upstream riparian vegetation, primarily alders and sycamores at 5,000 feet, along Tonto Creek in central Arizona. Water use by this streamside vegetation is high in summer and low in winter, when this photo was taken.

Table 1.—Potential and adjusted water yield increases (inches) and total area of each vegetation type, Upper Colorado River Basin

	Millions of acres	Potential increase	Adjusted[1] increase
Alpine	1.3	2 - 5	
Mountain grasslands	unknown	1.5 - 3	
Subalpine	6.8	1 - 3	[2]1 - 3
Aspen	3.2	3 - 5	0.3 - 1
Ponderosa pine	1.5	1 - 3	.1 - 1
Mountain brush	3.3	1 - 3	
Big sagebrush	17.6	0 - 1	
Pinyon-juniper	12.6	0 - 0.5	
Upstream riparian	unknown	6 - 24	

[1]*Adjustments reflect multiple use and other considerations.*

[2]*No reduction was indicated for subalpine forests because patch cutting, which tends to be most water productive, was also considered to be acceptable from multiple use and silvicultural standpoints. Under shelterwood, individual tree selection, or group selection harvest methods, water yield increases probably would be less than one-half these values.*

Table 2.—Potential and adjusted water yield increases (inches) and total area of each vegetation type, Lower Colorado River Basin

	Millions of acres	Potential increase	Adjusted[1] increase
Mountain grasslands	0.1	1.5 - 2	
Mixed conifer	.4	3 - 4	1 - 2
Aspen	.1	3 - 5	0.3 - 1
Pondersoa pine	6.0	1 - 3	1 - 1
Chaparral	3.5	1 - 5	2.4
Pinyon-juniper	19.9	0 - 0.5	
Upstream riparian	.1	6 - 24	

[1]*Adjustments reflect multiple use and other considerations.*

(water uniformly distributed over the treatment area) expected from manipulation of vegetation and snow. In commercial conifer forests—subalpine, mixed conifer, and ponderosa pine—treatment area refers to the entire working area where timber harvesting or other management practices are applied, including intervening trees, shrubs, or open areas which may receive some type of silvicultural treatment, or are left undisturbed. However, in the aspen, brushlands, pinyon-juniper, and upstream riparian zones, treatment area refers only to area cleared, converted, or otherwise modified; it does not include surrounding or intervening areas left untreated for wildlife, esthetics, or other purposes. A somewhat different interpretation of treatment area is applied to alpine, mountain grasslands, and high elevation sagebrush lands, where snow management is the water yield improvement method. Under these situations, treatment area refers to the snow source area (fetch) upwind of snow fences or other barriers, plus the downwind accumulation area where the snowdrift forms.

Variations in site capability, climate, and treatment methods determine the range of response in each of the vegetation types. The greatest response in streamflow can be expected on sites where large reductions can be made in evapotranspiration, whether this is done by trapping snow or by reducing vegetation. Clearcutting and type conversion are the methods that usually increase streamflow the most, except in the subalpine zone, where patch cutting is considered most water productive.

The vegetation type that offers the best opportunity for improving water yield in the Upper Basin is the subalpine, followed by aspen, mountain brush, and ponderosa pine. In the Lower Basin, the opportunity to improve the water supply is best in chaparral and ponderosa pine. Opportunities in mixed conifer and aspen are limited by the small acreage of these forests.

The potential for increasing water yield per unit area of treatment is greatest in upstream riparian vegetation, and is least in pinyon-juniper and sagebrush lands. However, the upstream riparian

areas are not likely to be the source of large amounts of additional water because the area is small and values are high for other uses that, for the most part, are not compatible with treatment practices required to accentuate water yield. Although big sagebrush and pinyon-juniper are extensive types, neither shows promise for improving water yield, except on the most favorable sites. While the potential appears greater in the alpine and mountain grasslands, the increases (tables 1 and 2) must be considered tentative, since they are based on increased catch of snow by snow fences on experimental sites. It has not been tried within an actual watershed.

Where clearcutting and type conversion are not acceptable, water yield response will be less than full potential, depending on the amount and methods of vegetation reduction. The potential increases for the mixed conifer, ponderosa pine, aspen, and chaparral vegetation types were adjusted for multiple use and other considerations (tables 1 and 2 and parentheses in table 3). The potential increases were reduced by one-half or more in all the commercial forest types, except the subalpine forests, where patch cutting, which tends to be most water productive, was also considered to be acceptable from a multiple use standpoint. Where patch cutting is not acceptable in subalpine forests, and other silvicultural systems, such as individual tree selection, group selection, or shelterwood methods, are used, the potential for increasing water yield may be less than one-half that expected from patch cutting (Leaf 1975).

Adjustments for mixed conifer forests reduced the potential increases from a depth of 3 to 4 inches to a depth of 1 to 2 inches over the area being managed, based on an assumed management strategy of periodic patch cutting to maintain about one-third of the area in small openings. In ponderosa pine, clearing away dense stands of trees can increase water yield by 1 to 3 inches over the areas cleared. However, management practices designed to provide an acceptable mix of forest products and other resources are expected to produce, on the average, only about 0.1 to 1 inch of additional water per year. The adjustments for aspen from 3 to 5 inches down to 0.3 to 1 inch reflects a somewhat arbitrary choice of clearcutting options, one at rotation age of 80 years for wood products (0.3 inch average annual increase for 80 years on the area actually clearcut) and the other at rotation age of 25 years to favor wildlife (1.0 inch average annual increase for 25 years on the clearcut portions). The adjustment in the potential increase for chaparral vegetation from 1 to 5 inches to an average of 2.4 inches for areas actually converted reflects lower onsite efficiency expected from a mosaic pattern of treated and untreated areas, and an estimate of offsite losses in transit to points of use downstream.

Water yield potentials for selected vegetation types are compared in table 3 with two previous evaluations in 1960 and 1974. The 1960 Senate Select Committee estimates pertain to the Southwest generally and the 1974 Ffolliott-Thorud estimates to the State of Arizona only. Current unadjusted estimates compare fairly well with the Senate Committee estimates in the subalpine, mixed conifer, aspen, and pinyon-juniper types, but are considerably higher in ponderosa pine and chaparral. However, the Senate Committee value of 0.5 inch of increased water yield for the ponderosa pine agrees with the current adjusted estimate of 0.1 to 1.0 inch. The higher projection for the chaparral in the current evaluation can be attributed to the favorable outcome of several brush conversion studies of the Arizona Watershed Program[6] conducted after the Senate Committee report in 1960. Similar tests in the pinyon-juniper vegetation failed to strengthen early projections for low increases from type conversion in this extensive cover type.

[6] *A cooperative research effort by federal, state, and water user interests was started in the 1950's to investigate the feasibility of increasing water yield in Arizona by manipulation of vegetation.*

Table 3.—Comparison of current evaluation of potential increases (inches) with other estimates

	Current evaluation	U.S. Senate 1960	Ffolliott & Thorud 1974 (Arizona only) Low option	High option
Subalpine	1 - 3	3.0		
Mixed conifer	[1]3 - 4 (1 - 2)	4.5	1.2	6.0
Chaparral	1 - 5 (2.4)	0.5	1.2	2.4
Ponderosa pine	1 - 3 (0.1 - 1)	.5	1.2	2.4
Aspen	3 - 5 (.3 - 1)	3.0	included with mixed conifer	
Pinyon-juniper	0 - 0.5	.25	negligible	

[1] *Figures in parentheses are adjusted to reflect multiple use or other considerations.*

The 1974 estimates by Ffolliott and Thorud are based on low and high treatment options in three vegetation types. Treatment in the mixed conifer forests would convert to grass one-third to two-thirds of the area next to stream channels. The low option projection of 1.2 inches of increased water yield from converting one-third of the area appears consistent with the current estimate of 3 to 4 inches from complete conversion, since response in this vegetation type appears proportional to area treated. However, the high option projection of 6 inches from converting only two-thirds of the forest appears overly optimistic. Treatment options in the chaparral would convert 40% and 60% of the area to grass for increases of 1.2 and 2.4 inches. These projections fall within the range of current estimates of 1 to 5 inches for an area fully treated (the average on favorable sites is 3.8 inches adjusted to 2.4 inches for onsite and offsite losses).

In ponderosa pine, the low option would clear one-third in strip cuts for 1.2 inches increase, and the high option would clear two-thirds in strip cuts for 2.4 inches increase. These are slightly higher estimates but not necessarily incompatible with current unadjusted estimates. However, since the current adjusted estimate of 0.1 to 1 inch is considered more realistic from a management standpoint, the water yield potential in ponderosa pine is believed to be much less than estimated for the Lower Basin by the Ffolliott-Thorud study. Further, the acreages considered suitable for treatment in the Ffolliott-Thorud study may not be available, since much of the ponderosa pine is in poorly stocked condition.

Assessment

Amount of Additional Water

The amount of additional water that can be produced within a multiple use management concept needs to be determined. It can be theorized that the maximum increase possible could be estimated by multiplying total acreage times the unadjusted average increase for each vegetation type (tables 1 and 2). If this were done in this study, some 4 million acre-feet would be indicated for the Upper Basin and about 2 million acre-feet for the Lower Basin.

However, this type of estimate ignores several basic problems that cause actual yield increases to fall short of the maximum potential.

1. Only a portion of each vegetation type could be treated economically for water yield increases. The amount depends on the demand for water and its value in the market place.
2. Consideration of other resource values and desires of the public tend to reduce both the area that can be treated and the effectiveness of treatments below that which could be obtained if water yield was the main objective of management.
3. The time frame required for water yield improvement practices to become fully operational is probably in the order of several decades for commercial forests with timber harvest rotation ages of up to 120 years. However, less time would be required for noncommercial types, such as chaparral.

Thus, the amount of water that can be produced by vegetation management can best be quantified in terms of a range of alternative management options that would include consideration of all factors above.

Another approach to assessing water yield potential is to determine how much treatment would be required to meet certain water augmentation goals. For example, the proposed Yuma Desalting Plant[7] on the lower Colorado River will produce up to 42,000 acre-feet per year of highly concentrated reject water, which would not be suitable for agricultural, municipal, or industrial uses. The Lower Basin states are unwilling to lose any water through a desalting plant reject stream because of anticipated future shortages. Therefore, the need arises to augment the existing supply by 42,000 acre-feet to make up the difference. Although vegetation management may not be the appropriate way to get the extra water, it is used here as an example to illustrate the role that vegetation management could play in augmentation of the surface water supply.

The 42,000 acre-feet could be obtained by placing 250,000 acres of subalpine forests in the Upper Basin under management designed for water yield improvement as a major objective. Or, the 42,000 acre-feet could be obtained by converting 210,000 acres of brush to grass in the Lower Basin. Larger acreages in each case might need to be treated, if water yield improvement practices should require modification to adequately accommodate other resource values.

As a second example, suppose it became necessary to augment the water supply of the Colorado River by 750,000 acre-feet per year on the average, with no restriction on where in the basin the water should be generated. Since the Upper Basin yields

[7] *Reject stream replacement study status report, January 1978, 102 p. USDI Bureau of Reclamation, Lower Colorado Region, Boulder City, Nevada.*

nearly five times as much water as the Lower Basin, it would be consistent to look to the Upper Basin for most of the extra water, say 500,000 acre-feet (3.5% increase), and to the Lower Basin for 250,000 acre-feet (8% increase).

In the Upper Basin, treatments as described earlier might be considered on the acreages indicated in table 4. The average increases projected for each vegetation type are arithmetic averages of the ranges in values shown in tables 1 and 2. Averages of the adjusted values were used for the aspen, mixed conifer, ponderosa pine, and chaparral types. In the Lower Basin (table 5), a larger percentage of the area would have to be treated to get the increases desired.

From these arbitrary examples of hypothetical treatments and acreages, it appears that 500,000 acre-feet of extra water could be generated in the Upper Basin by committing up to 22% of each vegetation type, except the aspen forests, in which 40% would be treated. The management strategy for the aspen type is 80-year rotation clearcut harvest in patches covering 20% of the total area plus 25-year rotation of patch cuts on an additional 20% of the total area.

Treatment on 22% of the subalpine forests including Douglas-fir, would produce 50% of the total increase. Mountain brush and aspen would be the next largest contributors. The increases attributed to the alpine zone and big sagebrush vegetation are projected with less certainty than for the other types because it is uncertain that these amounts of water can be generated on a watershed basis.

In the Lower Basin, more extensive treatments would be required to generate 250,000 acre-feet of extra water. Only small increases could be expected from snow management in the mountain grasslands and from patch cutting in the aspen, even if these cover types were fully treated. Also, because of the limited acreage of the mixed conifers, the potential for this type is small. Therefore, attention is focused on the chaparral and ponderosa pine forests, where 92% of the expected increase would be generated by treating about 20% of the chaparral and 33% of the ponderosa pine. Again, these acreages may not produce the desired amount of extra water if the suggested treatment practices should require modification to better accommodate other resource values.

Why not treat a larger percentage of chaparral, since the potential is good for increasing yield and the type is low in commercial value? First, large portions may not be treatable because cover is too sparse or slopes too steep, or because certain areas are classified for other uses such as wilderness. Also, the term treatment area as used for the chaparral refers to the actual area converted to grass or otherwise modified; it does not include surrounding or intervening areas left untreated for wildlife or other purposes. Therefore, treatment of 20% of the chaparral or mountain brush involves a much larger all-inclusive acreage than one in five, since untreated intervening areas may equal or exceed the acreage actually converted to grass.

However, availability of treatable acres is uncertain in all of the vegetation types. The arbitrary selection of treatable acreages used in this assessment should not be construed to mean that these acreages would be available for treatment. Treatable acreages may ultimately prove to be less (or more) than these, in which case the projected increases in water yield would also be different.

Cost of Producing Additional Water

Costs of initial treatment vary from a few dollars per acre to a few hundred dollars per acre, depending on the type of treatment and type of vegetation. Initial treatment cost figures are of limited value, however, in determining cost of increased water yield, unless tradeoffs are included and maintenance costs are properly evaluated over a period of years. Some of the treatment possibilities in the example given here may not now be economically feasible, although they might be at some later date.

Although few good economic evaluations are available, cost estimates indicate where low- and high-cost water could most likely be obtained. Generally, water derived from management of commercial forests is the least expensive, since relatively small additional outlays or tradeoffs are required to get the extra water. Several estimates made during the mid to late 1960's pegged costs of additional water from multiple use management of western forests at $1 to $5 per acre-foot. Estimates of costs of increasing water yield by type conversion in the chaparral ranged from $10 to $50 per acre-foot, the average being near $20. The cost of producing extra water by snow fences in alpine and mountain grassland areas has not been determined. However, some preliminary estimates[8] indicate that, on favorable sites, additional water might be obtained at costs of $10 to $20 per acre-foot. These costs would be higher today, although the relationship of cost to value of water may not have changed much.

In an economic analysis of chaparral conversion in central Arizona, T. Brown et al. (1974) con-

[8]*Martinelli, M., R. Tabler, and R. A. Schmidt. 1975. An estimate of snow management potential on Straight Canyon barometer watershed, Utah. 9 p., unpublished report. USDA For. Serv., Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.*

Table 4.—Hypothetical treatments and percentage of areas necessary to increase water yield in the Upper Basin by 500,000 acre-feet per year

	Millions of acres	Percent treated	Method of treatment	Average[1] increase	Increased yield
				(*inches*)	(*acre-feet*)
Alpine	1.3	5	Snow fences at 2,000 feet average spacing	3.50	19,000
Subalpine	6.8	22	Maintain ⅓ area in small patch cuts	2.00	249,000
Aspen	3.2	20	80-year rotation clearcuts with regeneration	0.33	18,000
		20	25-year rotation clearcuts with regeneration	1.00	53,000
Ponderosa pine	1.5	20	Reduce to and maintain 60-80 ft^2 basal area per acre by patch cuts, strip cuts, thinning	.55	14,000
Mountain brush	3.3	20	Type conversion to grass	2.00	110,000
Big sagebrush	17.6	5	Type conversion to grass combined with snow fences	.50	37,000
Total					500,000

[1]*Arithmetic average of adjusted or potential increases shown in table 1, except the aspen, which is explained in the section on aspen.*

Table 5.—Hypothetical treatments and percentage of areas necessary to increase water yield in the Lower Basin by 250,000 acre-feet

	Millions of acres	Percent treated	Method of treatment	Average[1] increase	Increased yield
				(*inches*)	(*acre-feet*)
Mountain grasslands	0.1	10	Snow fences at 2,000 feet average spacing	1.75	1,500
Mixed conifer	.4	33	Maintain ⅓ area in small patch cuts	1.50	16,000
Aspen	.1	20	80-year rotation clearcuts with regeneration	0.33	500
		20	25-year rotation clearcuts with regeneration	1.00	1,500
Ponderosa pine	6.0	33	Reduce to and maintain 60-80 ft^2 basal area per acre by patch cuts, strip cuts, thinning	.55	91,000
Chaparral	3.5	20	Type conversion to grass	2.40	140,000
Total					251,000

[1]*Arithmetic average of adjusted or potential increases shown in table 2, except the aspen and chaparral, which are explained the sections on aspen and chaparral.*

sidered costs and benefits of converting 850,000 acres of chaparral to grass. Annual benefits from the most favorable alternative were found to be (1) 0.21 acre-foot of increased water yield per acre of converted chaparral delivered downstream and valued at $12.50 per acre foot, (2) 0.24 additional animal-unit-month (AUM) per acre of grazing capacity valued at $6.51 per AUM, and (3) $0.34 per acre reduction in firefighting costs. The average per-acre annuity benefit ($4.49) minus the annuity cost ($1.98) left a net average annual return of $2.51 per converted acre (1972 prices).

While increased forage and reduced firefighting costs helped to defray cost of conversion and maintenance, the value of the increased water satisfied more than one-half of the total cost. Although the relative inputs from increased forage and reduced firefighting costs varied between areas, it seems reasonable to assume that in areas with a benefit-cost ratio greater than 1, additional water would be produced for less than its valuation of $12.50 per acre-foot.

The value of additional water is difficult to determine because of the complicated nature of water rights and laws governing water use and distribution in the Colorado River Basin. Seldom do economic principles operate freely to determine the price of water. In the above described economic analysis (T. Brown et al. 1974), the average value of additional water delivered to the Salt River Valley was estimated at $12.50 per acre-foot, including hydroelectric power revenues from water falling through the series of dams in the Salt River above Phoenix. The value of the additional water was based on the assumption that the primary user of any additional water in the Valley, at least to the year 2000, would be the agricultural sector—there being some unmet demand for water to irrigate low-valued feed grain and forage crops. All other, higher valued demands are already met. The marginal value of water (that is, the most the farmer could pay for additional water and still pay variable costs) was estimated at $11.20 per acre-foot (1972 prices) (O'Connell 1972, T. Brown et al. 1974).

The value of water may increase relative to other values and costs in the future as ground water depletes and demand for water increases as a result of anticipated population growth and energy development within the Colorado River Basin. In anticipation of future water shortages, the Central Arizona Project (scheduled for completion in the mid-1980's) will deliver Colorado River water to central and southern Arizona at a charge of at least $46[9] per acre-foot for municipal-industrial users. Since this price reflects willingness to pay, it is suggested that additional water from vegetation management may be equally valuable in certain areas.

Time Frame for Implementing Water Yield Improvement Practices

Long-range planning would be required to fully implement water yield improvement practices outlined in this report. In slow-growing forests of the subalpine zone, harvest rotations are of the order of 120 years, although full water yield potential could be realized sooner than the rotation age of forest trees. However, demand for wood products, physical limitations, and economic constraints, among others, will prevent rapid implementation of water improvement programs. For example, demand for aspen wood products is much too low for an annual harvest of aspen to sustain the water yield potentials projected in tables 4 and 5. Demand for aspen products is expected to increase (Wengert 1976), but the time frame is 25 to 40 years.

Some water yield improvement practices could be implemented within a few years; however, that would result in immediate augmentation of water supplies. Type conversion of brushlands to grass is the most promising approach for the Lower Basin, where the potential in the chaparral has been well researched, and is now in the pilot testing phase. Studies are needed in the Upper Basin to determine extent and applicability of similar treatments for the mountain brushlands.

Other Considerations

Many uses of the forest are compatible with efforts to increase water yield (fig. 16). Reducing forest cover also improves herbage production and can significantly reduce fire hazard in certain situations. Treatment may be beneficial for some species of wildlife and detrimental for others (Franzreb 1977). While scenic beauty usually suffers following treatment, the site tends to recover

[9] *In 1974, the Central Arizona Water Conservation District Board set tentative canal side charges for CAP water to M&I users at $32.50 per acre-foot plus $13.50 per acre-foot to cover operation, maintenance, and repair costs (for agricultural users these charges are respectively, $2.00 and $13.50). These charges can be expected to increase with inflation and other causes. Barr and Pingry (1977) estimated the required canal side charge to M&I users in 1976 dollars at $51 per acre-foot and the full economic cost at more than $100 per acre-foot, including operation, maintenance, repair, distribution, and treatment costs.*

toward (and may even exceed) previous esthetic levels (Daniel and Boster 1976). Further, some forest types, such as aspen, may best be regenerated by clearcutting, or some other form of stand reduction, that will promote development of vigorous new stands.

Although streamflow has been shown to increase as a result of treatment on numerous small experimental watersheds, there is no assurance that the water yield increases projected here can be physically demonstrated at downstream reservoirs or points of use even if transmission losses are negligible, since the increased flows may not be detectable by conventional measurement techniques after combining with flows from other sources (Bethlahmy 1974). The amount of water yield increase resulting from treatment must be taken on faith unless special gaging and statistical controls are implemented to verify the increases. Pilot demonstrations on watersheds of several thousand acres would help to verify the increases, and bridge the gap between the small experimental watershed and large-scale water yield improvement projects.

Weather modification to increase winter snowpack is also being considered as a means of augmenting the flow of the Colorado River. Atmospheric scientists involved in weather modification generally agree that snowfall can be increased in mountainous regions by 5% to 30%, with 10% an average prediction based on current technology.[10] The combined effects of weather modification and vegetation modification on the same area produce a synergistic interaction that increases streamflow more than if the two practices are applied separately. In essence, vegetation treatments become more efficient as precipitation increases. Assuming a 10% increase in winter precipitation from weather modification, the increased efficiency of vegetation management is expected to be in the range of 5% to 10%. Thus, there is justification for combining the practices, when possible.

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[10]*PSIAC Water Management Subcommittee. Herbert B. Osborn, chairman of task force report: "State-of-the-art in weather modification in the Pacific Southwest." April 1977. 10 p.*

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Water yield from forest and rangelands can be augmented by managing vegetation and snow to reduce evapotranspiration. Some arbitrary goals to increase water yield were chosen to illustrate the potential for increasing water yield, and treatments were hypothesized to get these increases.

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Choosing an Activity Fuel Treatment for Southwest Ponderosa Pine

Stanley N. Hirsch, Gary F. Meyer,
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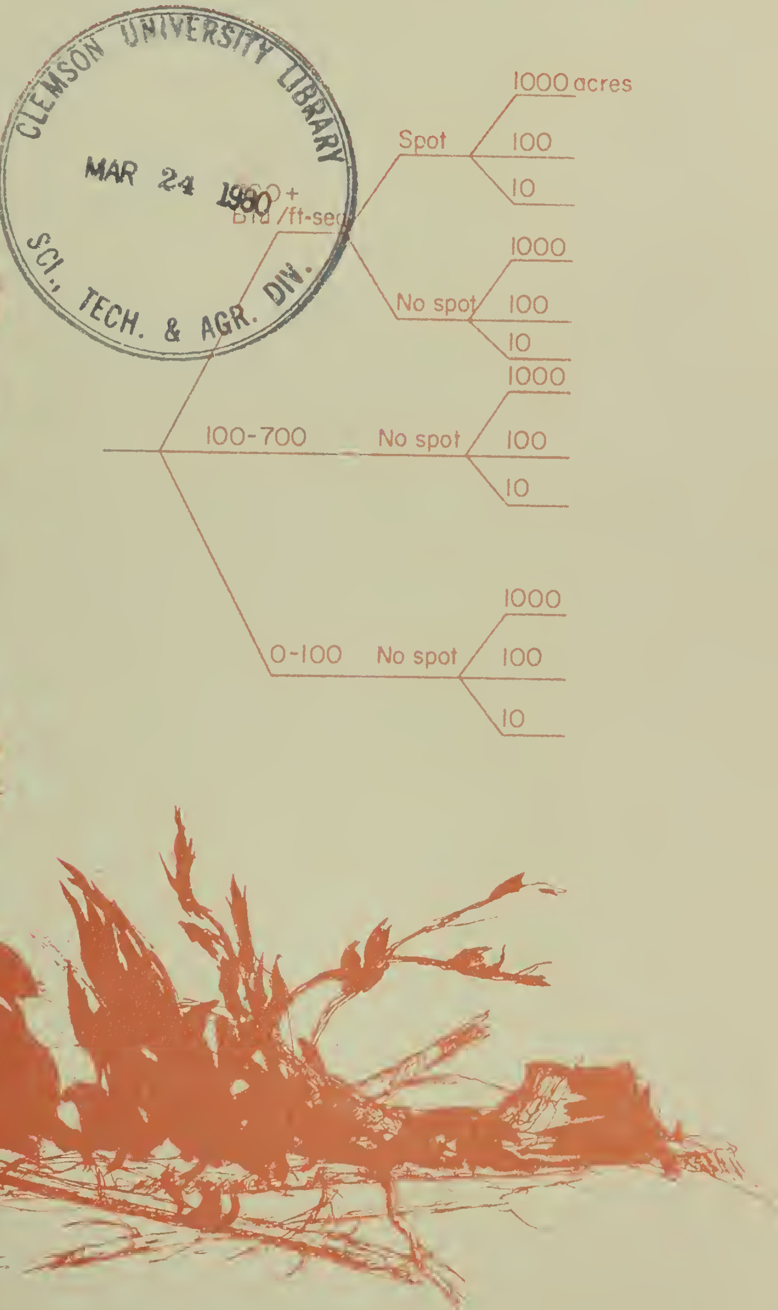

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Choosing An Activity Fuel Treatment for Southwest Ponderosa Pine

Stanley N. Hirsch, Engineer,[1]
Gary F. Meyer, Forester,[2]
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Abstract

Fire hazard projections using decision analysis, fuelbed-, fire behavior-, and probability-modeling on the Coconino National Forest indicate that, considering only timber-related cash flows, piling and burning sawtimber slash is the preferred fuel treatment for southwest ponderosa pine, although this treatment also has the highest expected annual burned acreage.

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Choosing an Activity Fuel Treatment for Southwest Ponderosa Pine

Stanley N. Hirsch, Gary F. Meyer, and David L. Radloff

The skyrocketing cost of wildfire-related activities is making wildland fuel management decisions increasingly important. Of particular concern is the fire hazard of residual debris from cutting operations. Accomplishing land management objectives may depend on treating large areas of such activity-fuel deposits using such tested treatments as fire, manual, or mechanical means to reduce fuel loadings.

The National Fuel Inventory and Appraisal Project has developed a general approach for evaluating fuel treatments. The approach combines state-of-the-art fuelbed-, fire behavior-, and probability-modeling in a decision analysis framework.[3] To test this method, a case study was conducted on the Woods Canyon Watershed, Mormon Lake Ranger District, Coconino National Forest (fig. 1). This paper discusses the fuel appraisal methods employed and the results obtained for fuel treatments proposed by forest personnel.

Study Area

The Woods Canyon Watershed contains about 12,000 acres of ponderosa pine forest—a mosaic of small, even-aged "stands" ranging from stagnated saplings to mature sawtimber (Ffolliott et al. 1968). Most of the even-aged patches are smaller than 1 acre. Surface fuels show a similar lack of uniformity. Average fuel loads in the area are light, but concentrations of heavy fuel exist which greatly influence fire behavior. The nonuniformity of forest cover and dead fuels presents special problems for fire hazard appraisal. The methodology discussed in this paper is designed for the heterogeneity typical of ponderosa pine forests.

Problem

The Coconino National Forest has a very high wildfire ignition rate. The Mormon Lake Ranger District alone experiences about 98 fires per year, or 1 fire for every 3,500 protected acres. A very effective fire suppression organization has kept most of these fires small. An unfortunate result of such effective fire suppression is an increase in dead fuel over large areas. Prior to the establishment of fire protection, repeated surface fires maintained natural fuels at lower levels and thinned dense pine reproduction.[4]

The addition of activity fuel (fuels created by man's activities) to these natural fuels is a major concern of local forest managers. Sawtimber harvesting, pulpwood harvesting, and precommercial thinning are planned for the entire Woods Canyon area and will add to existing fuel loads and increase fire hazard. Forest managers are considering five alternative fuel treatments to mitigate these effects:

1. Pile and burn sawtimber slash. (The local, very heavy slash concentrations from single-tree sawlog harvesting are not acceptable to area managers. These present high hazards immediately and result in jackpots which may persist for several decades. Because of this, piling and burning sawtimber slash is considered a minimum fuel treatment.)
2. Pile and burn sawtimber and thinning slash.
3. Broadcast burn the entire area by prescription prior to thinning.
4. Broadcast burn and use the burning to accomplish thinning.
5. Develop "clean" corridors and fuelbreaks to limit the size of escaped fires. (We did not formally analyze fuelbreaks as an alternative to direct fuel treatment. Unless fuelbreaks are very wide, they will not stop crown fires, nor will they prevent long-range spotting from propagating fire spread. In areas where access is poor, fuelbreaks may be effective in permitting quicker attack on fires.)

The important question is "What fuel treatment(s) will have the greatest net benefit?" The results of our analysis of acres expected to be burned by wildfire dur-

[3] *Hirsch, Stanley N., and David L. Radloff. A method for analyzing activity fuel decisions. U.S. Dep. Agric., For. Serv., Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. (in preparation).*

[4] *Dieterich, John H. 1976. Prescribed burning in ponderosa pine—State of the art. 18 p. Paper presented at Eastside prescribed burning workshop [Bend, Oreg., May 3-7, 1976]. U.S. Dep. Agric., For. Serv., Pac. Northwest Reg., Portland, Oreg.*

ing the next 21 years and present net worth of fire- and timber-related cash flows for the entire Woods Canyon sale area under four management alternatives are shown below. (Since clear guidelines are not available concerning the most appropriate interest rate for forest management investments, a 5% interest rate was used. The effects of different interest rates are discussed in a later section of this paper.)

	Expected acres burned by wildfire	Present net worth (5% interest rate)
Pile and burn sawtimber slash	1,126	$2.1 million
Pile and burn sawtimber and thinning slash	160	$2.0 million
Broadcast burn prior to cutting	542	$1.2 million
Broadcast burn to thin	542	$1.4 million

These results are discussed in detail below.

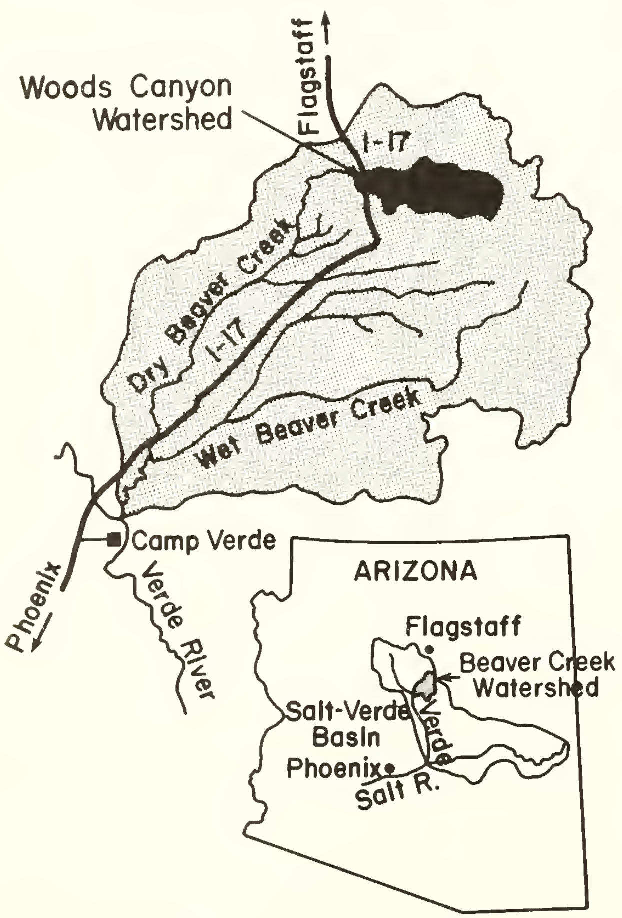

Figure 1.—Location of Woods Canyon Watershed (U.S. Department of Agriculture 1977).

Solution Framework

Evaluation of alternative treatment methods requires knowledge of how fire losses are affected by changing the fuel complex. In ponderosa pine relatively "cool" ground fires are easily suppressed and do little resource damage. Under present suppression policy only very hot fires escape attack and become large—often causing substantial damage. Therefore, fire size is a useful indicator of fire loss.

The procedure outlined in this paper estimates the probability a fire will exceed 10 acres for each fuel treatment alternative. Fires of less than 10 acres are considered small fires with little associated damage. Historical average size for fires larger than 10 acres (400 acres) is used to estimate the expected size if the 10-acre size is exceeded.

Large-Fire Process

Most large fires in the Woods Canyon area are caused by long-range spotting. Interviews with local fire management officers and fire researchers indicated that litter fires are usually kept small unless they produce long-range spot fires (over 1/8 mile). The interviews also revealed that where slash is absent, the firebrands causing spotting usually come from dense patches of sapling trees (doghair) which torch out. These doghair clumps have low crown bases, so most fuel concentrations in excess of normal litter fuel (fuel particles less than 1 inch in diameter) will produce flame lengths sufficient to ignite the crowns. Thinning the doghair clumps reduces the chance of clumps torching out, but the thinning slash can produce firebrands which are lofted above the canopy, causing long-range spotting as did the doghair clumps.

Spotting Model Before Cutting

A precutting spotting model can be represented as a race between the spot fire production/growth rate and fire suppression forces. The model asks, "Does a surface fire cause a doghair clump to torch out before the fire can be extinguished?" The answer depends on the surface fire spread rate, the distribution of doghair clumps and jackpots (concentrations of medium to heavy fuels sufficient to cause torching in doghair clumps), the rate at which firebrands are produced, and the speed of suppression forces.

The model estimates the probability a fire will escape initial attack and produce spot fires under specified fuel and weather conditions. The model assumes a fire will become larger than 10 acres if a spot fire generates a second, independent spot fire. This is discussed in more detail in appendix 1.

Additional assumptions concerning the spotting process are:

1. Long-range spot fires can be generated if the 10-hour timelag fuel moisture is ≤10% and the windspeed is ≥10 miles per hour. Under these weather conditions, a doghair clump which contains a burning jackpot will torch out.
2. An existing fire produces, at most, one new, independent, long-range spot fire.
3. Weather data collected at Pulliam Field near Flagstaff, Ariz., reflect weather conditions in Woods Canyon.

Spotting Model After Logging

The presence of numerous patches of thinning slash reduces the chance of suppressing ground fires. A fire no longer has to reach a point target (jackpot) to cause spotting; it has only to reach an area of thinning slash. Once the fire is into slash, there is little chance that it can be stopped until it burns through the entire patch. For thinning slash, the model assumes long-range spotting will occur if the 10-hour moisture is ≤10%, the windspeed is ≥10 miles per hour, and the fire is burning with a fireline intensity of at least 700 Btu/ft-sec. Based on the distribution of the areas to be thinned and modeled fire growth rates, the estimated probability is 0.83 that any fire would reach thinning slash. The derivation of sequential spotting probabilities for the slash situations is discussed in appendix 1.

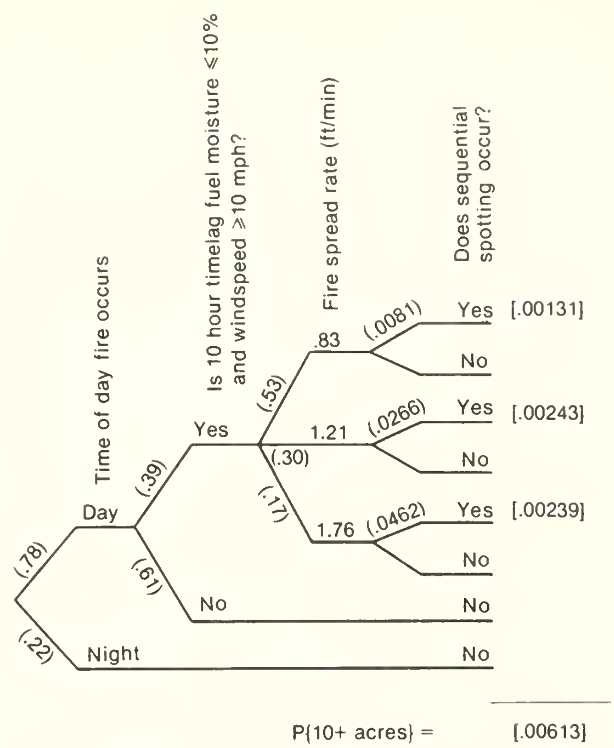

Figure 2.—Event tree used to estimate the probability that a fire will become larger than 10 acres. This tree represents existing fuel conditions with no activity-generated fuels. A number in parentheses is the probability that a particular event will occur. A number in brackets is the probability of a "large-fire" outcome.

Evaluation Methods

Evaluating a fuel treatment requires estimating the properties of the fuelbed it produces.

Prior to cutting, needle litter and woody fuels less than 1 inch in diameter are distributed rather uniformly over the entire area with concentrations of larger fuels locally superimposed on the fine particles.

Cutting superimposes a quantity of slash on the existing fuels. The amount and characteristics of activity fuels were estimated by procedures developed at the Northern Forest Fire Laboratory (Puckett et al. 1979; Brown et al. 1977; Albini and Brown 1978).

Prescribed burning prior to thinning reduces or eliminates some of the existing fuels. The effect on litter may be short-lived because of increased fall of scorched needles, but the effect on large fuels is longer lasting. A detailed description of each fuelbed used in this analysis is given in appendix 2.

For each fuelbed, Rothermel's (1972) fire spread model was used to estimate fire behavior over the range of fuel moisture and windspeed conditions experienced at Flagstaff. The model predicts expected fire spread rates and intensities (app. 1). In order to reduce this information to a single fuel appraisal "index," an event tree was formulated combining weather data, modeled fire behavior, and the large-fire spotting model. Evaluating the event tree yields the probability a fire will become larger than 10 acres.

Figure 2 illustrates the event tree for estimating large-fire probability prior to cutting. The first two nodes of the tree represent probabilities the specified weather conditions will be observed when a fire occurs. These probabilities were obtained from Flagstaff weather data (1970-76). The third node shows the probability a fire will spread at a particular rate. The last node shows the probability a fire will spot twice in sequence (or that a fire will be larger than 10 acres). The product of all probabilities along the path leading to a branch tip is the probability that outcome will occur. Summing for all the sequential spotting outcomes yields the probability that any fire will become larger than 10 acres.

The precutting event tree indicates a large-fire probability of 0.006. Historically, the proportion of fires

larger than 10 acres on the Mormon Lake Ranger District (which includes Woods Canyon) is 0.005. This correspondence between the model and actual observations indicates an analogous model may be useful in evaluating activity fuels.

An event tree to estimate large-fire probability in the presence of activity fuels is shown in figure 3. Nodes 1 and 2 concern weather criteria for spotting. The third and fourth nodes represent the distribution of sound or rotten jackpots. (For example, 70% of the Woods Canyon doghair clumps have an initial stocking of 1,000 stems per acre; of these, 40% can be expected to contain a sound-log jackpot.) The last node shows the probability that the fire will spot twice in sequence. In the example, the probability of a fire over 10 acres is 0.13—more than 20 times the probability without slash.

The results from modeling the conditions prior to cutting, cutting with no fuel treatment, and broadcast burning prior to cutting are compared in figure 4. These model results provide the information required to compare the effects of the various fuel treatments.

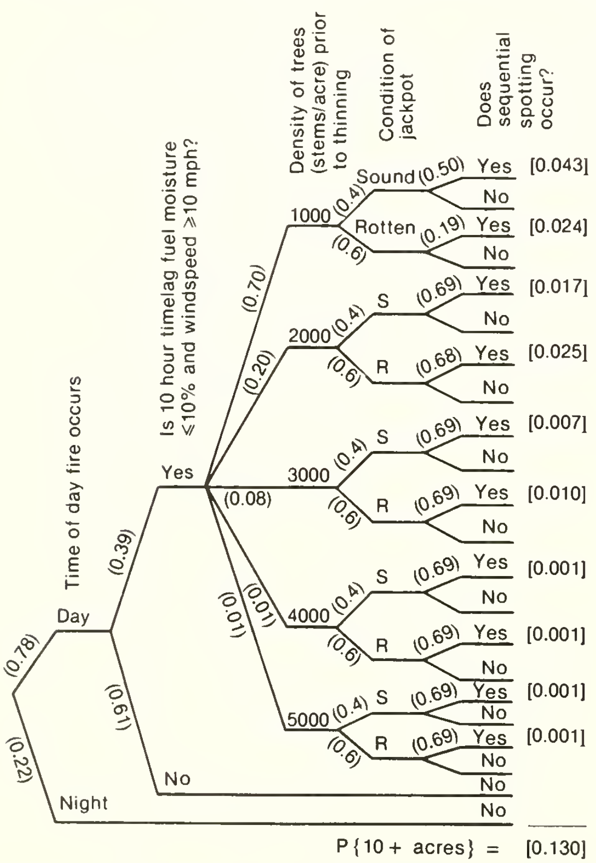

Figure 3.—Activity fuel decision tree to estimate the probability of occurrence of a fire larger than 10 acres. The fuelbed represented is untreated, 1-year-old thinning slash draped over large fuel concentrations. This tree represents the worst modeled fuel situation.

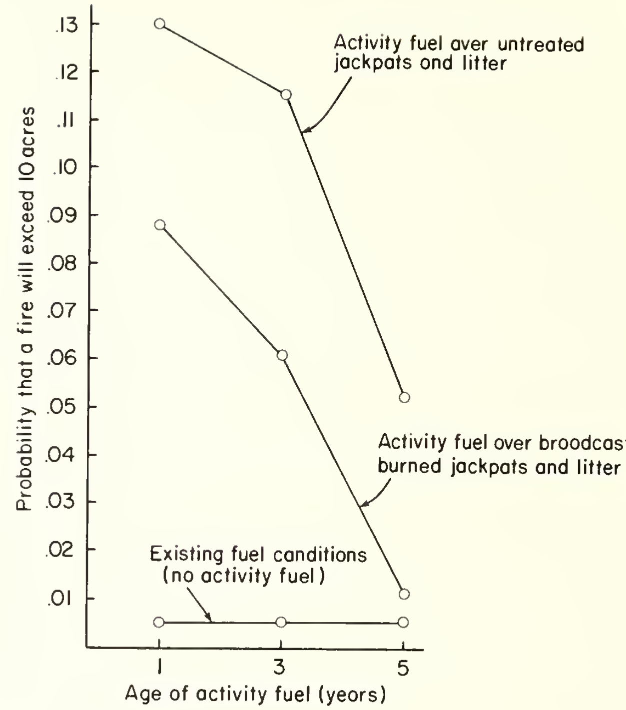

Figure 4.—Modeled large-fire probability under various fuel conditions. The decrease with time reflects the natural weathering of slash.

Expected Acres Burned

The expected annual burned acreage for each fuelbed (fig. 5) is the product of the annual number of ignitions, the probability an ignition will develop into a large fire, and the average size of a large fire. The Mormon Lake Ranger District fire occurrence rate of 1 fire per 3,500 acres per year indicates an expected occurrence rate of 3.4 fires annually for the 12,000-acre Woods Canyon area. Therefore, if no slash is present:

$$\text{Expected acres burned per year} = 3.4\ \frac{\text{ignitions}}{\text{year}} \times 0.006\ \frac{\text{large fires}}{\text{ignition}} \times 400\ \frac{\text{acres}}{\text{large fire}} = 8 \text{ acres.}$$

Expected burned acreage provides a means for comparing fuel treatment effectiveness.

Economic Analysis

One way to evaluate the alternative fuel treatments is by comparing their cash flows for the entire 12,000-acre area. To make this comparison, we need estimates of the value lost (or gained) because of fire and the value gained because of silvicultural treatments. The present net worth of the cash flow for each alternative will then reflect its economic merit.

Fuel conditions	Years from present	1	2	3	4	5	6	7	8	9	10	11-20	Total
	Existing fuel (no slash)	8	8	8	8	8	8	8	8	8	8	8	160
	Activity fuel over jackpots	178	156	154	152	69	68	68	67	67	67	8	1126
	Activity fuel over broadcast burned jackpots	120	83	82	81	16	16	16	16	16	16	8	542

Figure 5.—Expected annual burned acreage for the Woods Canyon Watershed under different fuel conditions. Third-year modeled large-fire probabilities were applied for years 2, 3, and 4; fifth-year probabilities were applied for years 5 through 10. After 10 years, non-slash fuel conditions were used in all cases. In estimating acres burned for the period shown, we assumed the same acre would not burn twice under wildfire conditions.

Evaluating the economic effect of a fire was simplified by considering only the effect on the timber resource. In the ponderosa pine type, fire damage is highly correlated with the number of acres which are intensely burned (Biswell et al. 1973). The large fire, burning with high intensity and often accompanied by crowning, causes most of the fire losses. For these fires, loss can be represented as the timber value per acre times the number of acres burned.

The sustainable timber harvest volume depends upon the silvicultural treatment applied and the number of acres which escape burning by high intensity fire. Under the proposed cutting regime for Woods Canyon (precommercial thinning, pulpwood thinning, and selection sawlog harvesting) the expected sustained harvest is 3,600 board feet per acre plus 3 cords per acre every 20 years. This represents a silvicultural optimum: any deviation will reduce timber production.

Table 1 describes the fuel models and activities associated with each fuel management alternative. The harvest volumes per acre in year 21 do not reflect fire losses. Actual dollar loss due to fire includes fire suppression costs and the value of the timber destroyed (we have assumed no salvage occurs). Based on past experience, the cost of suppressing fires larger than 10 acres is $500 per acre. Lost timber value is reflected in a reduced area of mature timber available at the next harvest.

The unit costs and values used in the economic analysis are as follows:

Sawtimber stumpage at year 21 (assuming a 2% annual real value increase and $140 present value)	$213/Mfbm
Pulpwood stumpage at year 21 (assuming a 2% annual real value increase and $6 present value)	$ 9/cord
Large fire suppression	$500/acre
Precommercial thin	$ 20/acre
Prescribe burn for fuel reduction	$ 10/acre
Prescribe burn for fuel reduction and thinning	$ 10/acre
Machine pile and burn sawtimber slash	$ 28/acre
Machine pile and burn pulp slash	$ 28/acre
Hand pile and burn precommercial thin slash	$ 42/acre

The cash flow over 21 years for the "treat only sawtimber slash" alternative is shown in figure 6. In year 1, the cost of machine piling and burning sawtimber slash is $336,000 ($28/acre x 12,000 acres). There is also a $240,000 precommercial thinning cost. First year timber revenues were excluded in order to evaluate present fuel treatments as investments in future stands. First year harvests would occur regardless of fuel treatments. In year 21, when the next cutting entry occurs, sawtimber revenue is $8,338,183 (3.6 Mfbm/acre x $213/Mfbm x [12,000 acres - 1,126 acres burned]) and pulpwood revenue is $293,598 (3 cords/acre x $9/cord x [12,000 acres - 1,126 acres burned]). Each year there is a cost associated with fighting the expected large fires. The first year this cost is $89,000 ($500/acre x 178 acres). Cash flows for the other alternatives appear in appendix 3.

Table 2 is a comparison of the present net worth (at 5% interest rate) and expected acres burned for each fuel treatment alternative. The "treat only sawtimber slash" alternative results in the highest present net worth, but it also has by far the highest burned acreage. Through just one cutting period, more than 9% of the watershed is expected to burn. The large burned acreage would probably reduce the sustainable harvest volume/acre under this alternative. The effect on present net worth of such a reduction in harvest volume is illustrated in the following section on sensitivity analysis.

Table 1.—Woods Canyon fuel management alternatives

Alternative	Fuel model used	1st year activities	10th year activities	21st year activities
Treat only sawtimber slash	Activity fuel over jackpots	Cut sawtimber and pulpwood. Pile and burn sawtimber slash. Precommercial thin.		Cut 3.6 Mfbm/acre sawtimber. Cut 3 cords/acre pulpwood.
Treat all slash	Existing fuel condition	Cut sawtimber and pulpwood. Pile and burn all slash. Precommercial thin.		Cut 3.6 Mfbm/acre sawtimber. Cut 3 cords/acre pulpwood.
Broadcast burn	Activity fuel over broadcast burned jackpots	Cut sawtimber.[1] Precommercial thin. Broadcast burn prior to cutting. Pile and burn sawtimber slash.	Prescribed maintenance burn	Cut 2.4 Mfbm/acre[2]
Broadcast burn to thin	Activity fuel over broadcast burned jackpots[3]	Cut sawtimber.[1] Broadcast burn prior to cutting to thin saplings. Pile and burn sawtimber slash.	Prescribed maintenance burn	Cut 2.4 Mfbm/acre[2]

[1]*No pulpwood is harvested under the last two alternatives because char resulting from broadcast burning makes trees unacceptable to local mills.*

[2]*Firm numbers for these yields were not available. The 21-year yields for alternatives 3 and 4 reflect the assumption that intermediate cutting can increase the yield by up to 50% (from personal communication with Bob Alexander, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado).*

[3]*This fuel model represents a conservative model for the "thin with fire" alternative, in that it should over-estimate fire intensities. When thinning is done with fire, the killed trees become part of the fuelbed gradually over time. The model assumes a "slash" bed is created immediately. Therefore, expected loss figures for alternative 4 should represent upper bounds.*

Year	1	2	3	4	5	6	7	8	9	10	11...20	21
Sawtimber stumpage												8,338.2
Pulpwood stumpage												293.6
Machine pile and burn sawtimber slash	−336											
Machine pile and burn pulpwood slash												
Precommercial thin	−240											
Hand pile and burn thinning slash												
Broadcast burn												
Suppression cost	− 89	−78	−77	−76	−34.5	−34	−34	−33.5	−33.5	−33.5	−4	
Total	−665	−78	−77	−76	−34.5	−34	−34	−33.5	−33.5	−33.5	−4	8,631.8
Present net worth	2,104.8											

Figure 6.—Twenty-one year cash flow for the "treat only sawtimber slash" alternative using a 5% interest rate. The values listed are in $1,000 units. Costs and revenues were assumed to occur at the end of each year.

Table 2.—Comparison of cash flows and acres burned for the fuel treatment alternatives over one cutting period (amounts in thousands of dollars)

	Treat all slash	Treat only sawtimber slash	Broadcast burn prior to cutting	Broadcast burn to thin
Present value of sawtimber	3254	2989	2099	2099
Present value of pulpwood	115	105	0	0
Present value of thinning costs	-229	-229	-229	0
Present value of fuel treatment costs	-1120	-320	-507	-507
Present value of suppression costs	-50	-445	-216	-216
Present net worth of alternative	1975	2105	1150	1379
Acres burned	160	1126	542	542
Percent area burned	1.3	9.4	4.5	4.5

The "total slash treatment" alternative shows the next highest present net worth. Since only 160 acres are expected to burn over a cutting period, this alternative would be best from a maximum wood production standpoint. There may also be associated with this alternative social values not reflected in the cash flow presented here. The large fuel treatment expenditure may be justified if the near-exclusion of large wildfires is a management goal.

The "broadcast burn before cutting" alternatives have the lowest present net worth values, although they become more favorable at higher interest rates (see sensitivity analysis). These alternatives would also be more favorable if a detailed stand growth/fire model were evaluated over a time frame longer than 21 years. There is strong evidence that the reintroduction of fire into the ponderosa pine forest community would reduce wildfire hazard over the long run (Biswell et al. 1973). Under a regime of periodic prescribed burning, wildfires would be less intense and more manageable. Broadcast burning after thinning might be a feasible fuel treatment alternative in this case, but it was not analyzed in this study.

Sensitivity Analysis

The preceding discussion accurately compares the alternatives if all assumptions and model outputs are correct. Since this may not be true, it is instructive to examine the effect on present net worth of varying the critical parameters over a reasonable range. The results of this sensitivity analysis are shown in figures 7 through 11.

Variations in Interest Rate

The relative rankings of the "total slash treatment" and the two "broadcast burn" alternatives are quite sensitive to interest rate (fig. 7). At 9% interest rate, the "broadcast burn to thin" alternative becomes second in ranking in terms of present net worth.

Variations in Acres Burned

All of the possible errors in fire modeling affect the predicted number of acres burned. Figure 8 shows the effect of uncertainty in this parameter. If the true burned acreage is one-half of the predicted values shown in figure 5, the ranking of alternatives is unchanged. However, if the true acreage is 1.2 to 2 times the predicted amounts, the "total slash treatment" alternative is favored.

Variations in Sapling Stand Density

Figure 9 shows that if the density of sapling stands exceeds about 1,500 stems per acre, the "total slash treatment" alternative has the highest present net worth.

Variations in Sustainable Harvest Volumes

As indicated earlier, the sustainable harvest volumes under several of the alternatives are uncertain. Figures 10 and 11 show the effects of this uncertainty. If the future harvest volume under the "treat only sawtimber slash" alternative is actually less than 95% of our assumed value due to the effects of the large burned acreage, the "total slash treatment" becomes the first choice. If the harvest volume for the "broadcast burn" alternatives are higher than our conservative estimate of 2.4 Mfbm/acre, these two alternatives become much more favorable and may even be preferred in terms of present net worth. Since the selection of an alternative is so sensitive to this parameter, more study is warranted concerning the relationship between broadcast burning to thin stands, hand thinning, wildfire damage, and timber yield.

Summary

A complete analysis of fuel treatments must ultimately involve economic consideration of the effects of fuel treatment on fire hazard, timber production, wildlife habitat, soil characteristics, water yield and quality, and recreation values. A major obstacle

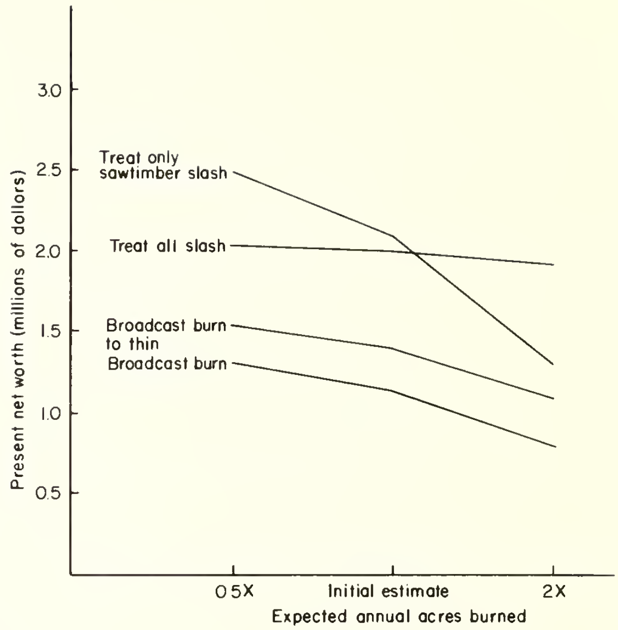

Figure 8.—Sensitivity of present net worth (at 5% interest rate) to variations in expected annual acres burned for all alternatives.

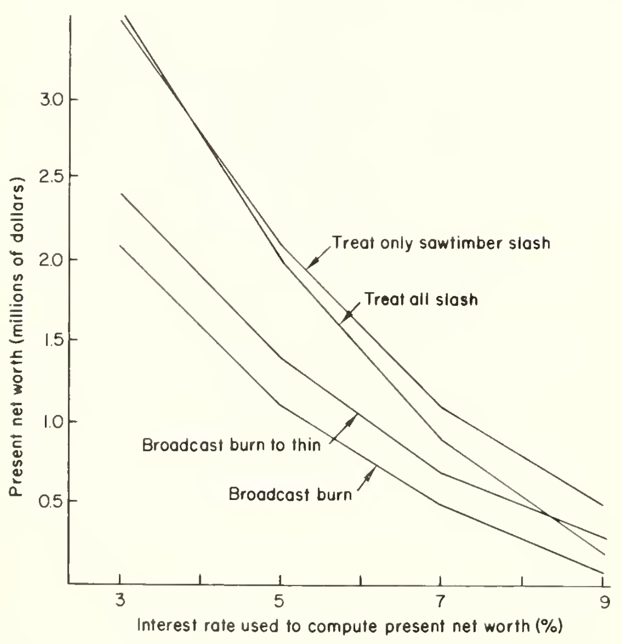

Figure 7.—Sensitivity of present net worth to variations in interest rate.

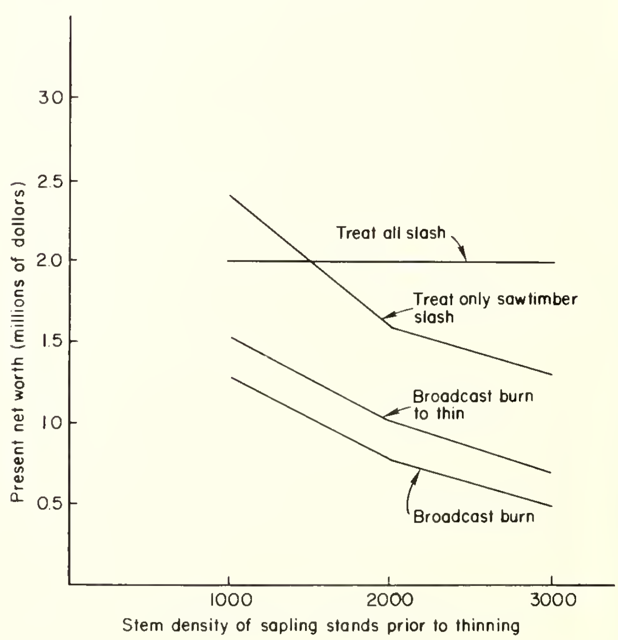

Figure 9.—Sensitivity of present net worth (at 5% interest rate) to variations in sapling stem density prior to thinning. Our initial estimate of average stem density is about 1,400 stems per acre.

has been the lack of a quantitative procedure for incorporating the fire hazard considerations. This case study describes an analytic procedure combining decision analysis, fire behavior modeling, and fuelbed modeling which provides the necessary fire hazard inputs. Fire hazard is described in terms of expected acres burned annually. The next step is to describe the effects of various fire regimes on resource production functions and operational costs.

For the Woods Canyon case study, only the effects on the timber resource are described. The economic analysis, using a 5% interest rate, indicates the minimum fuel treatment alternative (treat only sawtimber slash) appears to be preferred. As the sensitivity analysis indicates incorporating better timber production information or incorporating more resource values could change the selection of a fuel treatment. This reflects the fact that any decision can only be as good as the information used in the decision process.

The procedure outlined provides managers with the best available information concerning the fire hazard aspects of fuel treatments, and it clearly documents the factors involved in reaching a final decision.

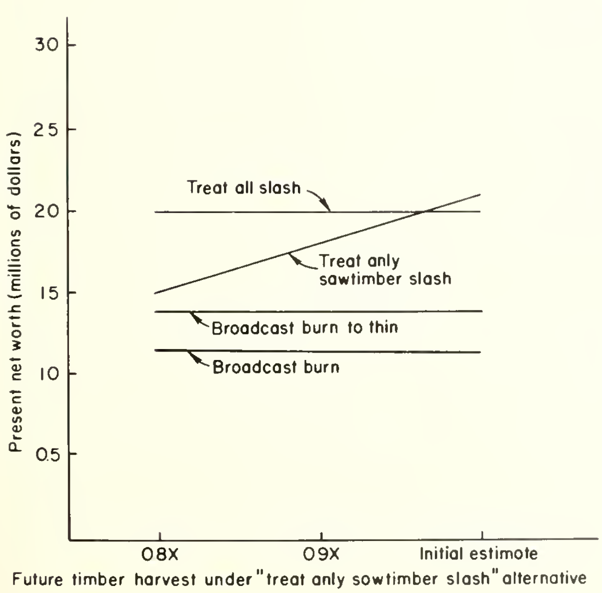

Figure 10.—Sensitivity of present net worth (at 5% interest rate) to variations in future sawtimber and pulpwood harvest volumes under the "treat only sawtimber slash" alternative where the initial estimate equals 3.6 Mfbm sawtimber and three cords pulpwood.

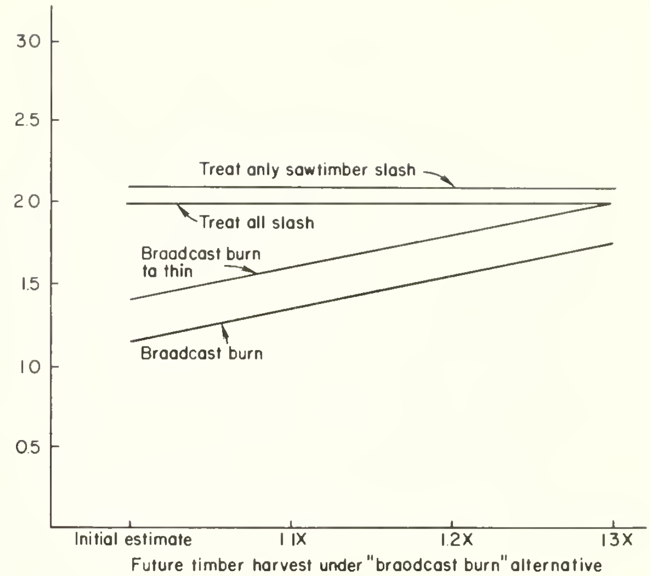

Figure 11.—Sensitivity of present net worth (at 5% interest rate) to variations in future sawtimber harvest volumes under the "broadcast burn" alternatives where the initial estimate equals 2.4 Mfbm sawtimber.

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Appendix 1
Large-Fire Spotting Model

The spotting model is based on the assumption that a surface fire will not spot unless it reaches a jackpot within a doghair clump of trees. We need to estimate the probability an initial fire reaches that point before suppression forces arrive. The assumption is made that if initial suppression forces arrive prior to torching, the fire will be contained at less than 10 acres. The chance of continuous spotting is dependent upon six factors:

1. Fire spread rate in the litter.
2. Density of doghair clumps which contain fuel concentrations (jackpots).
3. The lag time following ignition of a jackpot before torching occurs.
4. Time required for suppression forces to attack the initiating fire and spot fires.
5. Number of firebrands produced when a doghair stand torches out.
6. Probability that a firebrand causes an ignition.

Fire Spread Rate in Litter

Rothermel's fire behavior model (Rothermel 1972, Albini 1976a, 1976b) provides a method to estimate litter fire spread rates. Slope and wind strongly influence fire spread. We used zero percent as a representative slope. To estimate the wind near the combustion zone at the surface, we used one-fourth of the reported 20-foot wind measurement. The model assumes a fire is heading with the wind. Figure A1 shows the distribution of fire spread rates which were predicted for a litter fire based on fire-conditional weather data recorded at Flagstaff.

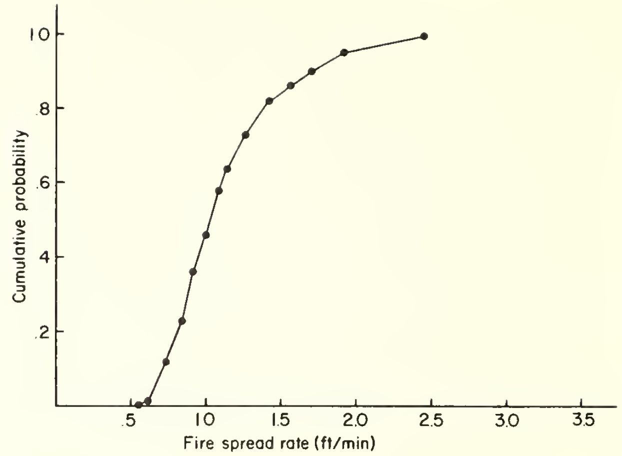

Figure A1.—Cumulative probability distribution of litter fire spread rates. The distribution was generated by executing the fire behavior model for daily fire-conditional weather conditions. Weather records were selected for days on which fires have occurred on the Mormon Lake Ranger District.

Density of Doghair Clumps

Line transect inventories were made to provide information about doghair stand and jackpot distributions. A straight line was walked through a sample area with the following data being recorded:

1. Total distance traveled (D).
2. Distance traveled through doghair stands (d).
3. Number of doghair stands (N).
4. Number of doghair stands with jackpots (n).

Assuming that doghair clumps are circular, the average distance traveled through a clump, d/N, is π/4 times the average clump diameter (the expected length of a cord of a circle is π/4 times the diameter of the circle), $\bar{w}$, or

$$\bar{w} = \frac{4}{\pi} \times \frac{d}{N} \qquad [1]$$

This average diameter represents the width of an imaginary belt transect used to sample clump density. The total area sampled is $\bar{w} * D$, so

$$\text{Density of doghair clumps } (\lambda) = \frac{n}{\bar{w} \times D} \qquad [2]$$

For the Woods Canyon area, the estimated density is 1.3 doghair clumps per acre.

Lag Time

The lag time between ignition of a jackpot and initiation of torching varies with changes in fuel configuration and fuel moisture. Personal observations indicate 10 minutes is a reasonable time.

Attack Time

Forest Service fire records include time elapsed from report of fire to the attack. Fire reports were used to determine the historical distribution of attack times for initial fires on the Mormon Lake Ranger District. Since attacking a long-range spot fire is similar to attacking an initially reported fire, the same distribution was used for attack times on spot fires. The distribution of attack times for fires on the Mormon Lake District is shown in figure A2.

Firebrand Production and Ignition Probability

When torching occurs and firebrands are produced, the number of spot fires is the product of two variables:

Number of long-range spot fires = (number of firebrands) x (probability a firebrand causes ignition) [3]

The probability a firebrand will cause an ignition is a function of fine fuel moisture and temperature,[5] but the number of firebrands is unknown. This situation prompted the assumption that when spotting occurs, only one new, completely independent fire is generated.

Assuming a random distribution of jackpots in the forest, the Poisson probability that a fire has reached j jackpots is:

[5]National Interagency Fire Center. 1977. Fire behavior affects control operations. Included in National interagency fire training course S-590—Fire behavior officer school, Marana, Ariz.

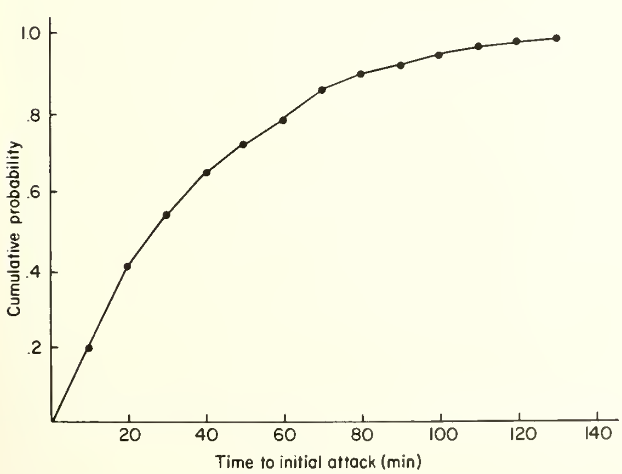

Figure A2.—Cumulative probability distribution of initial attack times for fires on the Mormon Lake Ranger District.

$$P\{j\} = \frac{(\pi r^2\lambda)^j e^{-(\pi r^2\lambda)}}{j!} \qquad [4]$$

where

j = number of jackpots within the fire's perimeter
λ = density of jackpots (number/square foot)
r = radius of fire (feet)

The probability that no jackpot ($j = 0$) has been reached by a fire is:

$$P\{0\} = e^{-(\pi r^2\lambda)} \qquad [5]$$

Alternatively,

$$P\{0,t\} = e^{-(\pi v^2 t^2 \lambda)} \qquad [6]$$

where

$P\{0,t\}$ = probability that no jackpots have been reached after t minutes of fire spread.
v = fire spread rate (feet/minute)
t = time since ignition (minutes)

Since the jackpot density, λ, is 1.3 jackpots/acre or $2.984 \cdot 10^{-5}$ jackpot/ft^2,

$$P\{0,t\} = e^{-9.375 \cdot 10^{-5} v^2 t^2} \qquad [7]$$

The cumulative distribution of attack times in figure A2 can be expressed as:

$$\int_0^t P\{\text{attack at time } t\}\, dt = 1 - e^{-.030t} \qquad [8]$$

The corresponding density function for attack time is:

$$P_a\{t\} = P\{\text{attack at time } t\} = .030e^{-.030t} \qquad [9]$$

We can use equations [7] and [9] to express the probability that a fire will be controlled before torching occures (P{control}). Recall that 10 minutes pass from the time a fire reaches a jackpot until tree crowns begin to torch out.

$$P\{\text{control}\} = \int_0^{10} P_a\{t\}dt + \int_{10}^{\infty} P_a\{t\}\, P\{0, t-10\}\, dt \qquad [10]$$

$$= \int_0^{10} .030e^{-.030t}\, dt + \int_{10}^{\infty} .030e^{-.030t} e^{-9.375 \cdot 10^{-5} v^2 (t-10)^2} dt \qquad [11]$$

$$= 0.26 + \int_{10}^{\infty} .030\, e^{-.030t}\, e^{-9.375 \cdot 10^{-5} v^2 (t-10)^2} dt \qquad [12]$$

By letting $u = t - 10$,

$$P\{\text{control}\} = 0.26 + \int_{0}^{\infty} .030\, e^{-.030(u+10)}\, e^{-9.375 \cdot 10^{-5} v^2 u^2} du \qquad [13]$$

$$= 0.26 + .022 \int_{0}^{\infty} e^{-9.375 \cdot 10^{-5} v^2 u^2 - .030\, u} du \qquad [14]$$

The integration in equation [14] was performed numerically for the three values of v in the event tree of figure 2. The results are as shown in table A1. Probability of spotting is 1.0 minus the probability of control before spotting. As indicated earlier, two spotting events in sequence is the condition for an escaped fire which will become larger than 10 acres. The chance of this joint occurence is:

$$P\{\text{sequential spotting}\} = P\{\text{spotting}\} \times P\{\text{spotting}\} \qquad [15]$$

For the case when thinning slash is present, the probability of sequential spotting, given that weather conditions are right for spotting, is:

$$P\{\text{sequential spotting}\} = P\{\text{fire reaches slash before control}\} \times P\{\text{slash fireline intensity} \geq 700 \text{ Btu/ft-sec}\} \times P\{\text{new fire reaches slash before control}\} \qquad [16]$$

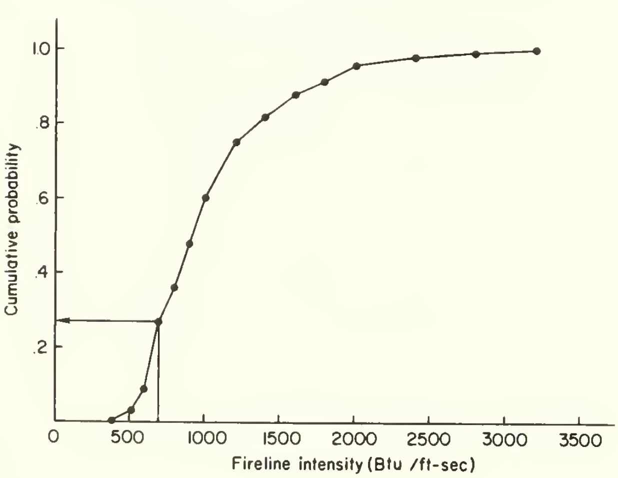

Figure A3.—Cumulative probability distribution of modeled fireline intensity for fires in activity fuel. The fuelbed results from thinning a 1,000 stem/acre sapling stand which contains sound-log jackpots. This graph shows there is a 0.73 probability that fire will burn with a fireline intensity exceeding 700 Btu/ft-sec.

Table A1.—Probability of sequential spotting

Spread rate (v)	P{control before spotting}	P{spotting}	P{sequential spotting}
(ft/min)			
0.83	0.910	0.090	0.0081
1.21	0.837	0.163	0.0266
1.76	0.785	0.215	0.0462

The probability that the slash fireline intensity exceeds 700 Btu/ft-sec was determined from cumulative probability curves, such as the example in figure A3, for each fuelbed condition.

The probability that a fire reaches slash before control is achieved was estimated by a procedure analogous to the determination of the probability of spotting in the "no slash" case discussed above. The probability is 0.83 that any fire will reach some slash before being controlled.

For the fuelbed situation represented in figure A3, then

$$P\{\text{sequential spotting}\} = 0.83 \times 0.73 \times 0.83 = 0.50 \qquad [17]$$

This number is entered as the topmost "sequential spotting" probability in the event tree in figure 3.

Appendix 2
Fuel Models

Fire behavior was modeled for one litter and two slash fuel situations. The fuel models are shown in table A2 and are discussed below.

1. **Existing fuel conditions (litter).**—This represents the fuel prior to harvesting. The true needle load can easily range from less than 1 to more than 3 tons per acre. Two tons per acre was selected as a representative load.[6] Fire growth rate estimates from this model were used in the analysis of both the preharvest conditions and the "treat all slash" alternative.

2. **Activity fuel over jackpots.**—This model represents the worst untreated slash fuel conditions. Fire behavior in the slash was modeled for activity fuels draped across existing jackpots. Because modeled fire intensities in precommercial thinning slash usually equal or exceed those in pulpwood slash, only the precommercial thinning cases were used for input to the decision trees. This avoids

[6]Personal communication with Steve Sackett, Research Forester, Rocky Mountain Forest and Range Experiment Station, Research Work Unit in Tempe, Ariz.

Table A2.—Natural fuel particle loads for the fuel models used for estimating fire behavior. The quantities of additional slash fuel for the last two models are shown in table A3

Fuel model	Particle size	Loading
	(inches)	*(tons/acre)*
Existing fuel (litter)	Needles	2.0
	0 to 1/4	[1]0.2
	1/4 to 1	1.0
Activity fuel over jackpots	Needles	2.0
	0 to 1/4	0.2
	1/4 to 1	1.0
	1 to 3	3.7
	3+ sound	Elevates fuelbed [2]19 in
	3+ rotten	Elevates fuelbed 9 in
	Plus slash fuel	
Activity fuel over broadcast burned jackpots	Needles	[3]1.5
	0 to 1/4	0.02
	1/4 to 1	0.10
	1 to 3	0.93
	3+ sound	Elevates fuelbed 5 in
	3+ rotten	Elevates fuelbed 5 in
	Plus slash fuel	

[1]All loads for 0- to 1/4-, 1/4- to 1-, and 1- to 3-inch woody fuels are based on data for Fort Valley Experimental Forest collected by John H. Dieterich and Steve Sackett. The average 1- to 3-inch load was increased to account for clumpiness in this size category.

[2]The elevating effect of jackpots is based on diameter measurements of more than 3-inch fuels at Fort Valley by Dieterich and Sackett. Sixty percent of all jackpots encountered were rotten; 40% were sound. We tripled the effective diameter of sound logs to reflect the fact that most sound jackpots still have branches intact.

[3]These figures are consistent with personal observations and prescribed burning results by Dieterich and Sackett. Davis et al. (1968) discuss increased needle accumulation following prescribed burning.

underestimating the large fire probability, since an initial ground fire may spread into both pulpwood and doghair slash. Estimation of slash amounts is discussed later in this appendix.

3. **Activity fuel over broadcast burned jackpots.**—This models the situation in which slash is created on top of existing fuels which have been prescribe burned. The slash is not treated. The model is used for the broadcast burning treatments.

Estimates of slash fuel quantities were based on stand analysis data[7] and individual tree weight tables (Brown et al. 1977). The stand tables represent average stem densities for rather heterogeneous areas, so the average densities for 2- and 4-inch trees (saplings) do not reflect the clumpiness which actually exists. To estimate the density within doghair clumps, we multiplied the average number of 2- and 4-inch stems per acre by 1/0.15, because sapling stands occupy about 15% of the Woods Canyon watershed.

Applying this factor results in the frequencies below:

[7]Unpublished data from Fred Larson, Research Forester, Rocky Mountain Forest and Range Experiment Station, Research Work Unit in Flagstaff, Ariz.

Density class interval	Relative frequency of occurrence
(stems/acre)	
0 – 1500	0.70
1500 – 2500	0.20
2500 – 3500	0.08
3500 – 4500	0.01
4500 +	0.01

Table A3 shows the calculation of slash loads for the five stocking classes. Thinning leaves 440 stems per acre (a 10- x 10-ft spacing). The distribution between diameter classes (before and after thinning) is 53% in 2-inch and 47% in the 4-inch d.b.h. class.

Appendix 3
Cash Flows for the Fuel Management Alternatives

Figures A4, A5, and A6 show the cash flows which characterize three of the fuel treatment alternatives. The cash flow for the "treat only sawtimber slash" alternative is shown in figure 6. A 5% interest rate was used in determining present net worth, and all costs and revenues were assumed to occur at the end of the appropriate year. Values in the figures are in thousands of dollars.

Table A3.—Estimation of activity fuel loadings. Activity fuel (slash) loads were computed from tree crown weight tables developed by Brown et al. (1977). The first four columns in this table include data from stand tables and thinning prescriptions. The fifth and sixth columns contain individual tree crown weight data. Tons/acre of slash (last two columns) are computed as the product of stems per acre cut and pounds per tree, divided by 2,000

Density class	Diameter class	Stems/ acre	Stems/ acre cut	Pounds/tree[1]		Tons/acre slash	
				<3 in	>3 in	<3 in	>3 in
1000	2	530	297	7.05	0.70	1.1	0.10
	4	470	263	23.8	12.0	3.1	1.60
2000	2	1060	827	7.05	0.70	2.9	0.29
	4	940	733	23.8	12.0	8.7	4.4
3000	2	1590	1357	7.05	0.70	4.8	0.47
	4	1410	1203	23.8	12.0	14.3	7.2
4000	2	2120	1887	7.05	0.70	6.65	0.66
	4	1880	1673	23.8	12.0	12.0	10.04
5000	2	2650	2417	7.05	0.70	8.52	0.85
	4	2350	2143	23.8	12.0	25.50	12.86

[1]*In determining tree weights by the method of Brown, Snell, and Bunnell, we assumed all the 2-inch stems and 60% of the 4-inch stems were classified as suppressed or intermediate.*

Year	1	2	3	4	5	6	7	8	9	10	11...20	21
Sawtimber stumpage												9,078.9
Pulpwood stumpage												319.7
Machine pile and burn sawtimber slash	−336											
Machine pile and burn pulpwood slash	−336											
Precommercial thin	−240											
Hand pile and burn thinning slash	−504											
Broadcast burn												
Suppression cost	−4	−4	−4	−4	−4	−4	−4	−4	−4	−4	−4	
Total	−1,420	−4	−4	−4	−4	−4	−4	−4	−4	−4	−4	9,398.6
Present net worth	1,975.1											

Figure A4.—Cash flow (dollars/acre) for the "treat all slash" alternative showing expected timber revenues, treatment costs, and suppression costs for a 21-year projection.

Year	1	2	3	4	5	6	7	8	9	10	11 . . . 20	21
Sawtimber stumpage												5,857.3
Pulpwood stumpage												
Machine pile and burn sawtimber slash	−336											
Machine pile and burn pulpwood slash												
Precommercial thin	−240											
Hand pile and burn thinning slash												
Broadcast burn	−120									−120		
Suppression cost	−60	−41.5	−41	−40.5	−8	−8	−8	−8	−8	−8	−4	
Total	−756	−41.5	−41	−40.5	−8	−8	−8	−8	−8	−128	−4	5,857.3
Present net worth	1,150.0											

Figure A5.—Cash flow for the "broadcast burn before cutting" alternative.

Year	1	2	3	4	5	6	7	8	9	10	11 . . . 20	21
Sawtimber stumpage												5,857.3
Pulpwood stumpage												
Machine pile and burn sawtimber slash	−336											
Machine pile and burn pulpwood slash												
Precommercial thin												
Hand pile and burn thinning slash												
Broadcast burn	−120									−120		
Suppression cost	−60	−41.5	−41	−40.5	−8	−8	−8	−8	−8	−8	−4	
Total	−516	−41.5	−41	−40.5	−8	−8	−8	−8	−8	−128	−4	5,857.3
Present net worth	1,378.6											

Figure A6.—Cash flow for the "broadcast burn to thin" alternative.

Hirsch, Stanley N., Gary F. Meyer, and David L. Radloff. 1979. Choosing an activity fuel treatment for southwest ponderosa pine. USDA For. Serv. Gen. Tech. Rep. RM-67, 15 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Fire hazard projections using decision analysis, fuelbed-, fire behavior-, and probability-modeling on the Coconino National Forest indicate that, considering only timber-related cash flows, piling and burning sawtimber slash is the preferred fuel treatment for southwest ponderosa pine, although this treatment also has the highest expected annual burned acreage.

Keywords: Fuel treatment, fuel appraisal, decision analysis

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BOTTINEAU
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WYO.
RAPID CITY
NEBR.
LARAMIE
LINCOLN
FORT COLLINS
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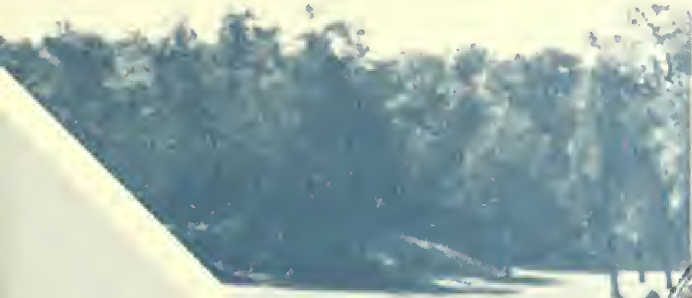
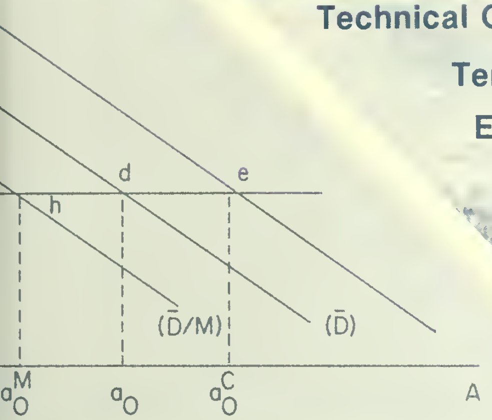
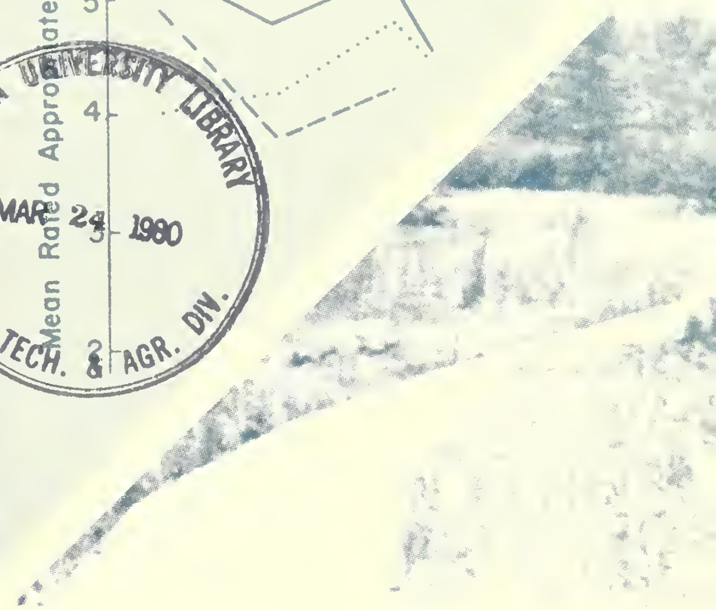
Assessing Amenity Resource Values







Technical Coordinators:

Terry C. Daniel

Ervin H. Zube

B. L. Driver

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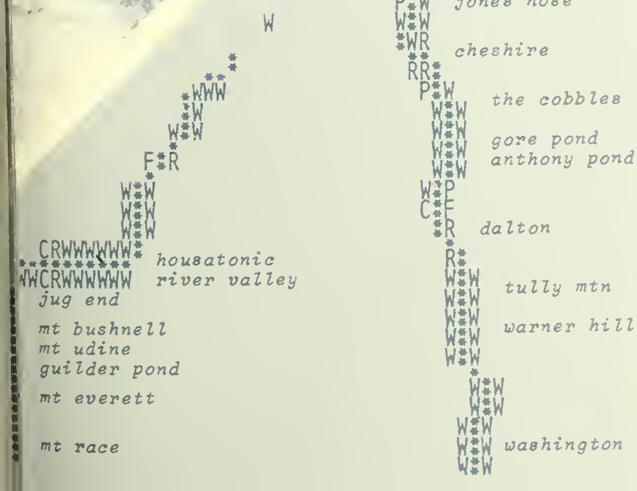

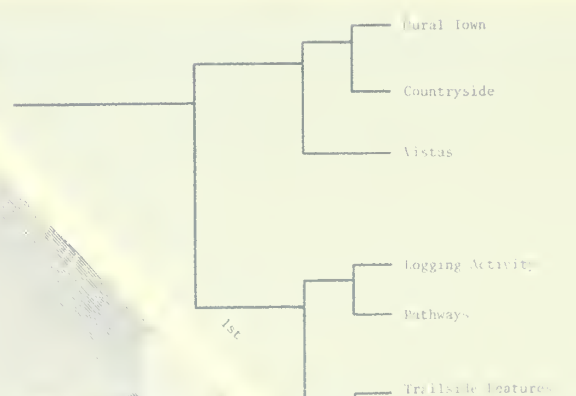

General Technical Report RM-68
Rocky Mountain Forest and Range Experiment Station
Forest Service
U.S. Department of Agriculture

ABSTRACT

Papers from a workshop and symposium at the Ninth Annual Meeting of the Environmental Design Research Association cover identifying environmental features responsible for perception of environmental quality, dimensions of wilderness experience, uses of wildlife, integrating user-based assessments with economic models, and the interface of natural and urban landscape elements.

The papers in this volume are published as submitted by the contributors, with minor editing by the technical coordinators. Each contributor is responsible for the accuracy and style of his or her paper. Statements of contributors may not necessarily reflect the policies of the U.S. Department of Agriculture.

General Technical Report RM-68

December 1979

Assessing Amenity Resource Values

Terry C. Daniel

Ervin H. Zube

and

B. L. Driver[1]

Technical Coordinators

[1] The technical coordinators are Professor of Psychology and Renewable Natural Resources, University of Arizona, Tucson; Director, School of Renewable Natural Resources, University of Arizona, Tucson; and Social Scientist, Rocky Mountain Forest and Range Experiment Station, Station's headquarters is in Fort Collins, in cooperation with Colorado State University.

FOREWORD

Managers of publicly owned forest and range lands are expected to carry out programs that provide the combination of goods and services that best meets social needs and preferences. The Multiple Use Sustained Yield Act, the National Environmental Policy Act, the Forest and Rangeland Renewable Resources Planning Act, the National Forest Management Act, and the Federal Land Policy and Management Act are clear in requiring all potential values--both commodity and noncommodity--be considered in assessments of alternative land management practices. To comply with these legal requirements managers must measure and compare the relative values of all possible outputs.

Increasing awareness of the importance of scenic beauty, nongame wildlife, wilderness, clean air and water, and other noncommodity products has revealed a lack of adequate information and methodology for comparing values of these outputs of management with values of commodity outputs such as wood fiber and livestock forage. Assistant Secretary of Agriculture M. Rupert Cutler referred to this problem in August 1978, when speaking at a conference in Missoula, Mont. He raised the question: "How do we balance a quantifiable commodity value and amenity values that elude quantifiable descriptions?"

Better understanding of noncommodity benefits of forest and range lands is critical to proper land management throughout the nation. Thus, the Rocky Mountain Forest and Range Experiment Station is pleased to have co-sponsored two symposia at the University of Arizona dealing with techniques for assessing noncommodity values of wildlands.

David E. Herrick, Director
Rocky Mountain Forest and
Range Experiment Station

CONTENTS

INTRODUCTION

This volume contains a series of papers representing a cross section of esthetic resource assessment and evaluation methods. The methods differ with respect to the particular esthetic or noncommodity resources to which they are addressed, and they are in different stages of development. There is, however, a central feature that all have in common--all are "user-based" methods: The basis of each method is some relatively direct expression of preference or value judgment by human "consumers" of esthetic resources.

The user-based approach stands in contrast to expert appraiser methods, where evaluation is entrusted to the judgment of one or a few trained or talented individuals. It also differs from arbitrary modeling approaches, where "weights" or relative importance values are assigned or derived based upon an often elaborate set of rational assumptions. User-based methods accept the fact that the value of any resource ultimately rests upon human needs and desires.

In the attempt to assess and evaluate esthetic or noncommodity resources, user-based methods refer rather directly to human preferences and desires. The quantity and quality of esthetic resources is assessed by rankings or by more sophisticated quantitative scales derived from expressed choices, ratings, or other judgments supplied by human observers. Evaluation, the assigning of comparable indices of worth to various quantities and qualities of esthetic resources, is also based upon expressed choices and preferences of "users." Often, however, additional assumptions and calculations are employed in an effort to make these evaluations commensurate with market-price values available for commodity resources.

Most of the papers contained in the following pages were originally presented at a symposium and a workshop held at the Ninth Annual Meeting of the Environmental Design Research Association at the University of Arizona in April of 1978. Papers by S. Kaplan, Palmer, Brookshire and Crocker, Wohlwill, R. Kaplan, and Schomaker were presented at a symposium on environmental esthetics. The papers by Haas et al., Shaw, and Arthur were presented at a workshop on current research on the esthetic value of wildlife. The initial paper by Daniel and Zube and the paper by King were prepared especially for this volume.

The papers by S. Kaplan and Palmer discuss different approaches to identifying specific features of the environment that may be responsible for the perception of environmental quality. Palmer presents a case study of a hiking trail environment that includes both purely natural and predominantly manmade elements. S. Kaplan's paper addresses several issues in the more general effort to identify and define the elements of the environment that combine to affect esthetic values.

The paper by Haas et al., presents the results of investigations into the dimensions of backcountry and wilderness experiences. Shaw and Arthur both discuss the relationships between consumptive (e.g., hunting) and nonconsumptive (e.g., observing) uses of wildlife.

Papers by Brookshire and Crocker and by King represent initial efforts at the difficult task of evaluation. Both papers discuss the integration of user-based assessments with economic models and methods to develop commensurate values for esthetic resources.

Wohlwill addresses the interface of natural and urban elements in the landscape. Both Schomaker and Wohlwill use landscape simulation techniques to assess the effect of alternative management proposals for manmade elements on the perceived scenic quality of different natural landscapes.

R. Kaplan describes the development and application of an environmental quality assessment method that was found useful and effective in the context of both natural and urban landscapes.

Schomaker presents a study of natural landscape esthetics, and the effect of various landscape modifications on observers' perceptions of scenic beauty.

Together, the papers in this volume characterize the ongoing effort to develop reliable and effective methods for assessing and evaluating noncommodity resources. These efforts must be viewed as the beginning of progress on this essential task--much has been accomplished, but much remains to be done if esthetic and other resources are to be allocated rationally to meet the wants and needs of our society. It is our hope that bringing this important work together in one volume will facilitate coordination and cooperation among the many disciplines and investigators working on noncommodity resource assessment and evaluation.

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University of Arizona

ASSESSMENT OF ESTHETIC RESOURCES

Terry C. Daniel and Ervin H. Zube[1]

All resources are defined in terms of their ability to meet human needs or fulfill human desires. In this respect, esthetic resources, including landscape scenic beauty, wildlife, and the opportunity for outdoor recreation and wilderness experiences, are no different from the more traditionally recognized resources such as wood, water, and minerals.

Man's need for esthetic resources, in the biological or survival sense, may not yet be established, but there are increasing indications that pleasant scenery and solitude and quiet provided by natural landscapes have positive effects on physical and mental well-being. Certainly the human desire for beautiful landscapes and undisturbed wildland areas is well established and is documented by numerous legislative acts. The value of esthetic resources, then, is ultimately determined by the wants and needs of society, as is the value of any other resource. There are, however, some significant differences in the way in which the benefits of esthetic resources are realized.

Many natural resources are appreciated indirectly. The benefits of standing timber in the forest, for example, may not be realized until it is converted to lumber and a house is constructed in some distant city. Complex systems of harvesting (or extraction), processing, transportation, and exchange intervene between wood, minerals, and many other basic resources and the consumer who finally receives the benefits of those resources. The benefits of esthetic resources, on the other hand, are generally realized directly by the "consumer." The perceptual experience afforded by a view of a beautiful landscape, or a tranquil moment near a mountain stream, or a chance glimpse of some wild creature in its natural habitat has immediate personal value for the perceiver. Only the observer's own perceptual system intervenes between the resource and his appreciation of it.

Perhaps the most important distinctions between esthetic and other resources arise in the attempt to evaluate them. The value of a mineral deposit or of a standing tree (as a lumber source) is typically determined by its price in some appropriate market. The market pricing system provides a quantitative (dollar) value for a great many goods and services, including many natural resources. These dollar values can be compared across resource categories. Esthetic resources, however, have not traditionally been part of the market system, and it has proven very difficult, if not impossible, to evaluate them in the same manner as market or commodity resources.

The need to assess and evaluate esthetic resources arises largely because of their intimate relationship with traditional market or commodity resources. When trees are harvested from a forest for use as lumber and fiber, their removal has an effect on the scenic and wilderness values represented by that forest. Alternatively, if a forest area is set aside for wilderness, the implication is that the noncommodity resources represented have more value to society than the commodity resources that are foregone. While the market place provides a means for determining gain achieved or foregone by harvesting or not harvesting a forest, there is currently no generally accepted means for determining the amount of loss or gain in esthetic benefits.

Similar trade-offs almost invariably occur between other commodity and esthetic resources. Further, there are frequently important trade-offs among noncommodity resources--as when increasing wildland recreation opportunities by providing better access for more people threatens to degrade scenic beauty and/or wilderness values. If rational decisions are to be made in these situations--rational in the sense that the alternative with the greatest net value to society will be chosen--systematic, reliable assessments must be made of the value of esthetic resources.

To assess the value of esthetic resources (or any resource for that matter) these resources must first be identified. This task has to some extent already been accomplished--the National Environmental Policy Act and a number of other national, regional, and state laws and policies have identified many important esthetic resources. Landscape scenic beauty, wildlife, wilderness, outdoor recreation, esthetic aspects of the air, water, and sonic environment, and symbols of cultural, historical, or archeological significance have all been specifically identified in protective legislation. While these acts do not provide detailed definitions, they have at least generally identified noncommodity resources that contribute to social welfare and individual well-being.

1/ The authors are Professor, Department of Psychology, and Director, School of Renewable Natural Resources, University of Arizona, Tucson.

After an esthetic resource has been identified, the quantity and quality of that resource must be determined before values can be assigned. The economic concept of supply and demand recognizes the essential role of the "amount available" in determining value. If landscapes of great beauty abounded in virtually limitless supply throughout the country, the value of any particular scenic area might be rather low. If beautiful landscapes are scarce, each area of high scenic beauty must be held as much more precious. Therefore, in order to evaluate esthetic resources, means must be found for assessing the available quantities of different grades (high to low quality) of landscapes, wildlife species, wilderness areas, recreation opportunities, and other noncommodity resources. For example, to determine the value of a specific forest landscape as a scenic resource, the quality of that landscape must be determined; i.e., whether it is extremely beautiful (more so than 90 percent of all landscapes of this type) or only moderately so. The available "supply" of landscapes of that type and quality must then be assessed before the question of value, relative to other goods, services, and resources can be approached.

Value, as it is being used here, is a strictly relative term. The value of one resource can only be understood by reference to the value of some other resource. To determine relative values, resources must be assessed in commensurate terms--determing whether producing 100,000 more acre-feet of irrigation water per year is more or less valuable than sustained production of 10 million board feet of lumber requires that the value of each alternative be expressed in some common terms, such as dollars. To make such comparisons, either the noncommodity resources must be evaluated in market-price terms, or some other common measure of value must be found that can be applied to both alternatives (e.g., units of energy expended or conserved, politically determined "importance," or some other commensurate gauging scheme).

Evaluation of esthetic resources poses significant philosophical and ethical questions, but assessment and evaluation methods are of much more than just philosophical interest. Resource managers, and in a broader sense society as a whole, are daily faced with questions requiring difficult choices between commodity and noncommodity resources. Currently there is no straight-forward way to deal with these questions. A major obstacle is the lack of suitable methods for assessing the quantity and quality of esthetic resources and for evaluating them in commensurate terms with other social values. Substantial progress is needed in the development of esthetic evaluation methodologies if these resource allocation questions are to be answered in a way that will serve the social good.

CONCERNING THE POWER

OF CONTENT-IDENTIFYING METHODOLOGIES[1]

Stephen Kaplan[2]

Environmental psychologists are often asked questions such as "How do people experience the environment?" or "What matters to people in the environment?" Clearly the answer to such questions involves preference, but it does not involve only preference. It also concerns the issue of what people find salient in a given scene, the issue of that content which transcends a given scene and provides a basis for responding to a whole group of scenes in a similar fashion.

People react to what they experience (and presumably the outdoor environment is no exception) in terms of commonalities, in terms of classes or categories. Any scene is perceived as a particular instance of a larger class of scenes. What class it is an instance of is not necessarily obvious. A given scene, for example, might be expected to be categorized quite differently by a park manager, a park visitor, a farmer, a forester, a landscape architect, a real estate agent, and so on.

Knowing the basis for identifying content used by the general public is not merely of theoretical interest. It is essential if we are to generalize beyond the boundaries of a particular study, as well as being of great value in making comparisons across different studies and across environments. Content is, of course, not a novel consideration in research on landscape esthetics. Most often, however, it is defined on a priori basis by the investigator. Some classification systems are based on land form and land use, others on management practices, and so on. Unfortunately, effort is rarely made to determine whether such expert-determined categories also serve as categories for the general public. One study making such a comparison showed little relationship between what the experts generated and what the public perceived (R. Kaplan, 1977a).

METHODOLOGICAL CONSIDERATIONS

If one wishes to discover the categories of environmental content that people respond to, there is no way around providing test subjects with a great variety of scenes to categorize. Defining a category is dependent upon multiple instances. While the importance of environmental sampling is widely recognized in principle, in studies of landscape esthetics it is often slighted. In some cases the problem stems from a desire to examine too many types of scenes, forgetting that each type needs replication. Further, having many people react to many scenes readily leads to an overwhelming quantity of data. There is the justifiable fear that such a study could never be analyzed, and if analyzed, never written up, and if written up, never understood.

Fortunately, there is a straightforward solution to the problem. A set of Content Identifying Methodologies (CIM) can be used to identify meaningful content groupings and partition the many instances into a few groupings. Ideally the resulting groupings are not only manageable, but also interpretable and communicable. As the examples I shall mention later suggest, in our experience this hope has been borne out in practice.

There are limits on how much one can ask research subjects to do. With, say 30 to 50 scenes, one cannot very well ask the subjects to rate each one on many different scales. This raises problems for traditional semantic differential procedures. However, asking people for a simple preference judgment works out very well. It is something that people do easily and quickly, it provides solid data for CIMs, and the choice itself constitutes information one presumably would want. Utilizing a broad sample of scenes and a simple preference judgment, it is effective to use two different CIMs. A nonmetric factor analysis and a hierarchical cluster analysis, used together have been found effective. Each CIM works well alone, and they work well together. They provide complementary information, together yielding a larger picture than would be possible with either alone (R. Kaplan 1974, 1975).

1/ Paper presented at the symposium on environmental esthetics at the Ninth Annual Meeting of the Environmental Design Research Association, University of Arizona, Tucson. April 10, 1978. I would like to thank Roger Ulrich, Thomas Gallagher, William Hammitt and Eddie Anderson for permission to use their results and photographs in this paper. The work reported here was supported in part by the Northcentral Forest Experiment Station, Forest Service, USDA.

2/ The author is Professor of Psychology at the University of Michigan, Ann Arbor.

SOME ILLUSTRATIVE STUDIES

The CIM methodology has been applied to a number of different environments. For the most part studies have been focused upon natural or largely natural settings. Across five studies (Ulrich 1973, Gallagher 1977, Hammitt 1978, Anderson[3/] and R. Kaplan 1977a) the CIMs employed yielded a total of 27 content categories or dimensions. Initial inspection of these dimensions suggests a rough distinction between those dominated by particular or special content (6 dimensions) and those where the spatial configuration is the organizing theme. The latter are futher divided into four types. A dimension is, of course, defined by multiple scenes, some four to eight in most of the instances considered here.

PARTICULAR CONTENTS

Particular content dimensions are often defined by the context of a particular study. For example, Gallagher (1977) found buildings in a natural setting seem to constitute a particular content (fig. 1, top left). In other studies buildings seem to have a particular content property not necessarily shared by other human-produced elements such as bridges, parking lots, and fences.

One of the dimensions in Hammitt's (1978) study of a bog environment also focuses on the built component in the natural setting. Here, various scenes which included a boardwalk -- a distinctive aspect of a relatively undifferentiated environment -- are grouped together (fig. 1, top right).

Another basis for a particular content category is special knowledge of the population being studied. If there are several scenes representing a single, characteristic type of environment in the area, these may form a dimension even though they are not that similar visually. For example, Anderson (1978) developed a "red pine forest" dimension (fig. 1, bottom left), a configuration well known to local residents.

In R. Kaplan's storm drain study, one dimension included what drain engineers call "impoundments," even though the participants in the study would have been unlikely to have heard the word in that context (fig. 1, bottom right).

The existence of these categories is consistent with the recent emphasis in a number of behavioral fields on the importance of things in human perception and thought. Anthropologists such as Pfeiffer (1972) and Campbell (1974) have pointed to subjects' ability to separate things out of a physically continuous environment as an important facet of human evolution. The importance to the thought process of mental representations of things in the world has increasingly been recognized by cognitive psychologists such as Posner (1973) and Rosch (1977). The use of "thing" in this context is somewhat abstract. It refers not only to pick-up-able entities, but also to other patterns of experience that are sufficiently separable and coherent to be subject to isolation and manipulation, at least in the mind if not also in the world. In this cognitive sense of "thing," buildings, bodies of water, and red pine forests all constitute good examples.

SPATIAL CONFIGURATIONS

Even more striking than the particular content dimensions, however, is the number of dimensions for which no such distinctive content could be identified. In these cases it is the spatial configuration of the scene that appears to account for the groupings. The "space" in question here is not the two-dimensional space of the picture plane, but the inferred three-dimensional space of the scene which the photograph depicts.

The central role of space in landscape content groupings did not come as a total surprise. There had been indications of the importance of space, (R. Kaplan 1973, S. Kaplan 1975) and the concept of mystery, a powerful predictor of preference, is inherently spatial. Mystery is based on the idea of information gained by going deeper into the scene. Implicit is the notion that certain scenes are appreciated for what it would be possible to do in them. Thus in the case of mystery, "Potential action" is critical to its role in preference. There appears to be a sound basis on theoretical grounds for extending this notion to other spatial configurations as well.

Consider, for a moment, the informational approach to understanding human nature. From this point of view, a human is an active, anticipating organism, always evaluating and preparing to cope with new situations (Kaplan & Kaplan 1978). Presumably, this evaluation and preparation are based in part on the presence of wild animals or other dramatic dangers. But presumably also, there is an evaluation in terms of the possibilities for and limitations of action. An important aspect of a new situation must be what it makes possible, what it permits one to do.

The idea of a rapid, automatic, unconscious evaluation as a component of the perceptual process has recently received support from an unexpected direction. Gibson (1977) has introduced into his framework the concept of "affordance." An affordance is what an object offers the perceiver, or in other words, what the perceiver would be able to do with the object. The concept of "potential actions" is, of course, quite similar, except that it applies to scenes and spaces rather than objects.

[3/] Doctoral dissertation in progress, Univ. Mich.

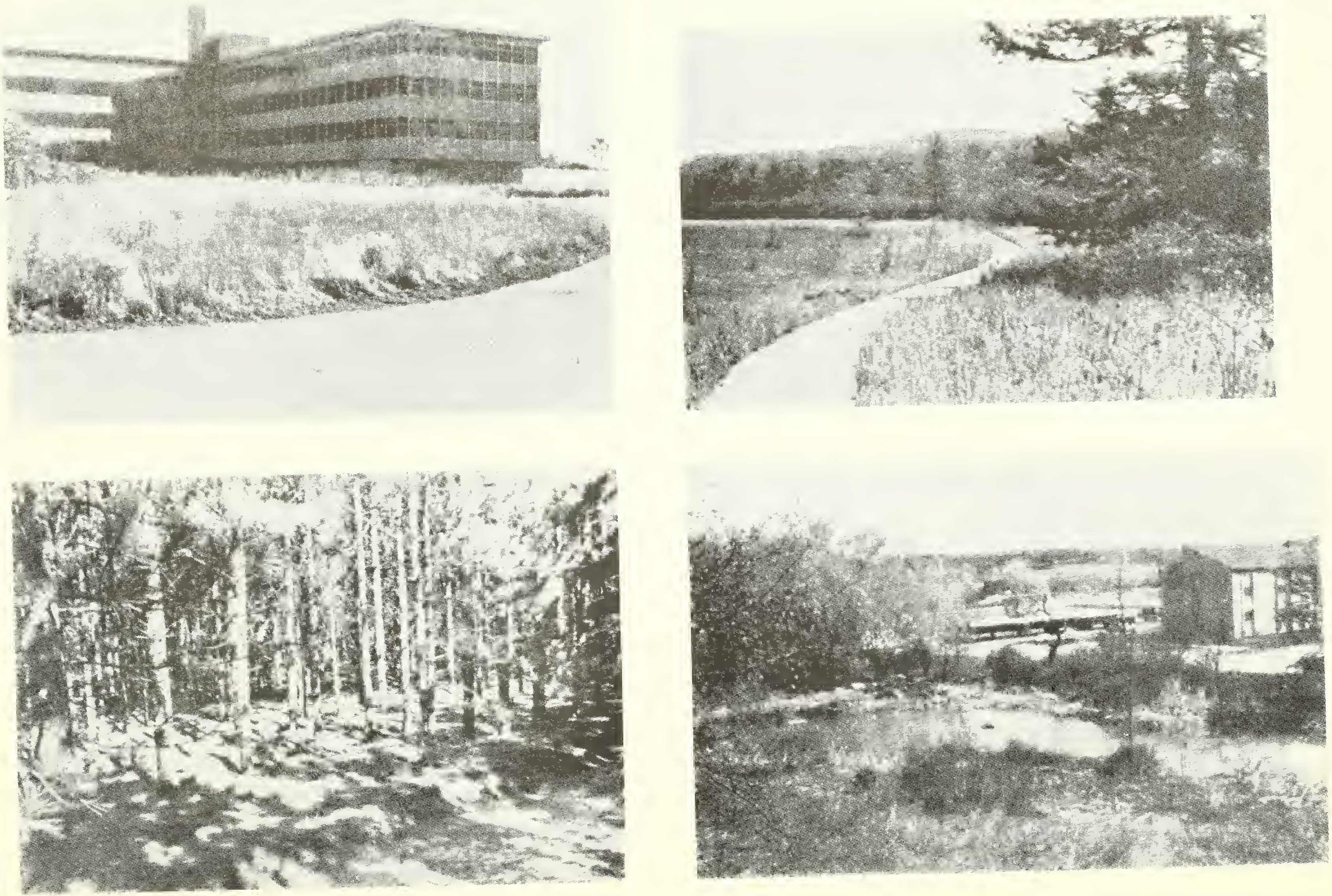

Figure 1.--Examples of specific content dimensions from four different studies.

Open, undefined scenes

Whether the scene is "deep" or "shallow" (S. Kaplan 1975) is likely to provide some grouping information about potential actions. The studies under discussion here, however, indicate the spatial component is considerably more complex than that. One such complication is the matter of how the space is defined. Some landscapes are not clearly either deep or shallow; they are flat, open, and in general lacking in spatial definition. Although the "quantity" of landscape on the picture plane between the foreground and the horizon is generally as great as in any other grouping of landscape photographs, these scenes lack depth cues.

Dimensions of depth are not uncommon in these studies; all but one of the studies had such a grouping. Ulrich's (1973) roadside study (fig. 2, top) is rather typical of this group. R. Kaplan's (1977a) scenic highway study yielded a dimension of depth (fig. 2, bottom), which is quite similar to a dimension from Anderson's forest practices study (fig. 3, top left). A second forest practices dimension, focusing on the visual impact of clearcutting, also falls in this grouping (fig. 3, top right). The dimension from Hammitt's bog environment study fitting this grouping represents a physical environment quite different from the others -- it depicts the bog mat itself (fig. 3, bottom). However, visually it is similar in form to other examples of the depth dimension.

The interpretation of the open, undefined spatial configuration in terms of "potential action" is necessarily rather negative. The very lack of spatial definition makes such scenes difficult to evaluate. There are insufficient cues to know exactly what actions are or are not possible Even a clear judgment as to the distance involved in traversing such an area is hard to make. Such settings reliably receive low preference ratings.

Spacious, well structured scenes

In marked contrast to the open, undefined configuration is the spacious, well structured configuration. The five studies include five such dimensions, two in one study and one in each of three. Trees play an important role in structuring the space in these scenes. In the example from the R. Kaplan scenic highway study (fig. 4, top left) and the Ulrich's roadside study (fig. 4, top right), the near trees play a central role. The other dimension from the Ulrich Roadside study belonging in this grouping depends on trees at a somewhat greater distance from the viewer to structure the space (fig. 4, bottom left) as does the example from the R. Kaplan drain study (fig. 4, bottom right).

These scenes through their greater depth suggest room to operate, places to go, opportunities for locomotion. Given such opportunities for action, one would expect these dimensions to receive high preference ratings, as, in fact they do.

Enclosed scenes

A particularly interesting type of grouping involves spatially well-defined dimensions with relatively limited depth. All these examples provide a sense of enclosure; they contain a screened or protected area in which one might hide. They are not, however, in the nature of cramped one-person hiding places. In fact, most of them seem to offer at least enough room to hide a small car.

Since "enclosure" is as much a functional distinction as a purely visual one, it is perhaps not surprising that the visual forms that seem appropriate to this grouping are highly diverse. There are seven such dimensions, with each of the studies represented. The dimension from the Anderson forest practices study is in a relatively heavily wooded area (fig. 5, top left). The Hammitt bog environment contributes a dimension both more open and more complex (fig. 5, top right). Two dimensions in this grouping come from the Gallagher naturalized landscape study. For one of these, the enclosure is created by fairly complex configurations of natural elements (fig. 5, bottom left). For the other, elements of the built environment combine with natural features to create the scenes of enclosure (fig. 5, bottom right).

From the "potential action" point of view, the enclosure type of spatial configuration is perhaps the most fascinating of all. Here one is promised a place of respite, a place of relative safety. One is provided with what Appleton (1975) in his perceptive analysis of landscape appreciation has called "refuge." Here, in other words, is an opportunity to escape notice, to see without being seen. Certainly an environment offering such an amenity would be desirable. However, "enclosed" groupings are not uniformly preferred. Some may be visually too unspacious, or lack definition.

Blocked views

The final category of spatial configurations is blocked scenes, where visual access is prevented. There are relatively few instances of these in the example studies. There are four such dimensions, two from the Ulrich roadside study (fig. 6, top), and a heavily forested grouping from the R. Kaplan scenic highway study (fig. 6, bottom). The prairie dimension from the Gallagher naturalized landscape study also falls in this grouping; in this instance the tall prairie grass itself created a perceptually blocked space.

Unlike the "enclosed" settings, the blocked ones prevent visual surveillance. They make it difficult to find a direction in which to proceed. One would expect such settings to be avoided

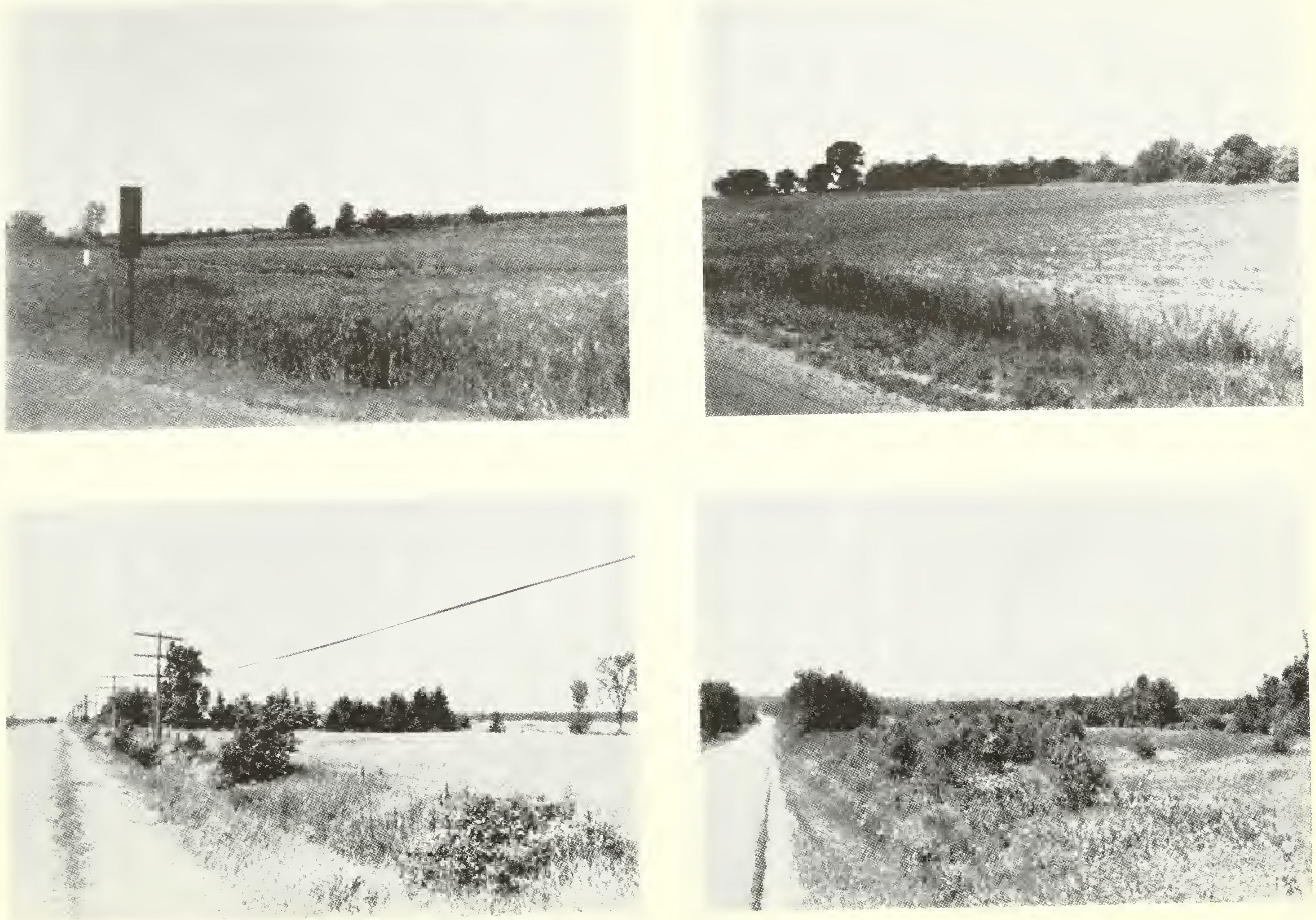

Figure 2.--Examples of open, undefined spaces from the roadside and scenic highway studies.

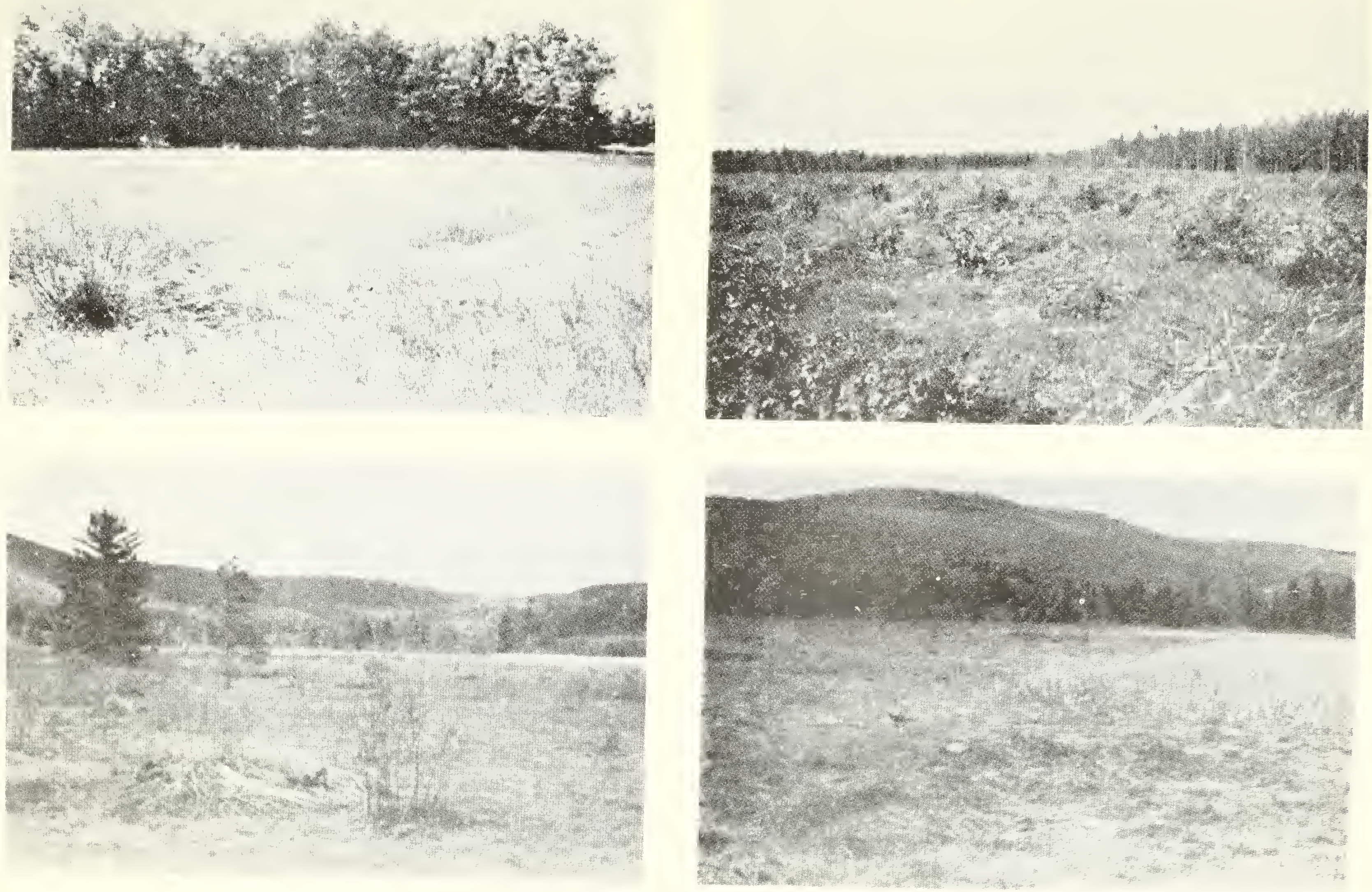

Figure 3.--Examples of open, undefined spaces from the forest practices and bog environment studies.

Figure 4.--Examples of spacious, well structured scenes from three different studies.

Figure 5.--Examples of enclosed scenes from three different studies.

Figure 6.--Examples of blocked views from the roadside and scenic highway studies.

on survival grounds and to be low in preference, as they in fact are.

The powerful role of visual access is strikingly demonstrated by this category of spatial configurations. A setting dominated by tall grass may not actually be impenetrable, but it looks as if it were. The embankment, which is impenetrable -- although one might climb over it -- is reacted to similarly. In addition to not seeing how one would go, and to not being able to visually evaluate the space as a whole, tall grass and rough foliage scenes appear to be even shallower than is in fact the case. Fine textures, near surfaces, by contrast, tend to enhance the sense of depth -- in general, coarse textures are perceived as closer and fine textures as more distant. This is a familiar phenomenon to creators of Japanese gardens and, for that matter, to mowers of American lawns.

SOME REFLECTIONS ON CONTENT

Let us return to the question with which this paper began. What do people find salient in a given scene? What is it that results in a whole group of scenes being responded to in a similar fashion? There are many ways to categorize a particular environment. Use of content-identifying methodologies and preference ratings by untrained participants yields categorizations that are distinctly different from those generated by various professionals. The meaningful groupings identified permit comparisons across diverse studies.

Another interesting property of the groupings is how profoundly informational they have turned out to be. The majority of the expert-generated category systems have little to do with the way people process information. Results of the example studies suggest that what people experience as salient in the landscape involves informational patterns (R. Kaplan 1977b, Kaplan & Kaplan 1978) readily interpretable in terms of requirements for adaptive behavior.

The way space is organized provides information about what one might be able to do in that space. A relatively brief glance at a scene communicates whether there is room to roam or whether one's path is blocked.

Thus, there appears to be both an empirical and a theoretical basis for categorizing landscape scenes. As is often the case with a satisfying research experience, these categories would have been hard to anticipate, but in retrospect make intuitive sense. These findings may also play a useful role in the further development of landscape assessment research. In a recent review, Stokols (1978) argues that generalizing findings across different settings requires a "theoretically based taxonomy of environments." The identification of consistent and interpretable patterns across a variety of different settings constitutes a first step toward developing such a taxomony.

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THE CONCEPTUAL TYPING OF TRAIL ENVIRONMENTS: A TOOL FOR RECREATION RESEARCH AND MANAGEMENT[1]

James F. Palmer[2]

Backcountry recreation is on the increase in this country. It is estimated that by 1980 a total of 120 million Americans will each spend an average of 24 days per year participating in walking-related activities (U.S. Senate 1974). One of the great recreation challenges in the near future will be to make adequate numbers of trails available for hiking and related activities.

There is an increasing need for systematic research to aid land managers in the selection of new trails and the management of existing trails. There is a growing body of backcountry recreation research (Clark 1977, Marsh 1971, Stankey and Lime 1973), but the most comprehensive studies have focused on only a few areas; the Great Lakes region (Lucas 1964, Stankey 1973), the Rocky Mountains (Stankey 1973), and the Pacific Northwest (Hendee et al. 1968) have attracted the most attention. The Appalachian Trail, in spite of its high frequency of use, has attracted only a few localized studies (Bolduc 1973, Murray 1972, Sargent 1969).

While committed to being responsive to user needs (National Park Service 1978), the Appalachian Trail Project Office of the National Park Service is understandably hesitant to base decisions on recreation patterns in western wilderness areas. The Appalachian Trail is thought to be a fundamentally different type of resource. Although the Trail is over 2,000 miles in length, it is normally considered to be only a few hundred feet wide. Even though it is one trail, it leads hikers through a diversity of environments. Each of these environments contributes to the trail's character; each provides a different setting for experiences; each is suitable for different activities.

There is a need for a procedure by which Appalachian Trail environments can be classified into types that are useful for management and planning purposes. Previous recreation research has not produced an adequate trail classification system reflecting user perceptions.

In cooperation with the U.S. Forest Service and the American Conservation Association, the National Park Service engaged the Institute for Man and Environment at the University of Massachusetts to develop an appropriate procedure for classifying Appalachian Trail environments. The management utility of that procedure is to be demonstrated by a pilot application in Massachusetts. The preliminary findings of this study are reported here.

METHOD

Trail Inventory

During July and August 1977, the author hiked the Massachusetts section of the Appalachian Trail to establish personal knowledge of the study area. A conscious attempt was made to experience a variety of climatic and hiking conditions. A field diary was kept to record trail experiences and encounters with other hikers and local residents.

Two different strategies were used to compile a photographic inventory. The first strategy was essentially random. Photographs were taken systematically at half-hour intervals during actual walking time. At each stopping point, two nonoverlapping photographs were taken at random angles. These random photographs provide a sample of trail conditons and surroundings as experienced by a hiker passing through Massachusetts. The second strategy was essentially subjective. Photographs were taken of distinctive environments that the investigator felt represented particularly important aspects of the trail. This subjective record generally captured "rare" conditions not adequately represented in the random inventory. The time and place of each photograph was logged as part of the field diary.

1/ Paper presented at the symposium on environmental esthetics at the Ninth Annual Meeting of the Environmental Design Research Association, University of Arizona, Tucson. April 10, 1978. Appreciation is expressed for the constructive criticism and editorial assistance of Ellen McClelland Lesser and Douglas Owen. This research was conducted under a grant from the American Conservation Association, National Park Service, and USDA Forest Service, for which Hugh C. Davis and D. Geoffrey Hayward are principal investigators.

2/ The author is with the Institute for Man and Environment, University of Massachusetts, Amherst.

Sorting Trail Environments

The data for classifying trail environments into types were derived from judgments made by ten respondents. The respondents were environmental professionals in disciplines ranging from the visual arts to policy planning and natural resources management to psychology. Their personal experiences with the outdoors ranged from day hikes through the New England countryside to weeks-long expeditions in the Alaskan Brooks Range.

Borderless color prints (3 1/2" x 5") of the 369 photographs taken in the inventory were shown to each respondent, allowing as much time as necessary to become familiar with the scenes. Each respondent was asked to:

> Sort the photographs into piles which you feel represent essentially similar kinds of trail environments...You may make as many or as few piles as you want, with as many or as few photographs in each pile as you want... The idea is that photographs are put together if they represent the same general type of trail environment so different piles will represent different trail environments.

When the sorting task was completed to each person's satisfaction, they were then asked to:

> Describe in your own words the important characteristics of that environment. Then, describe the sorts of activities or experiences which you expect to occur to hikers in this environment.

All categorizations and descriptions were recorded on coding sheets for subsequent analysis.

Cluster Analysis

Cluster analysis is the generic term for the numerical methods of classification used in this study to identify distinct types of trail environments. Essentially, the analysis determines the degree of empirical relationship between each possible pair of objects using an appropriate measure of association between the variables. The most closely associated pair is joined or "clustered" and is treated as a new object. The process is repeated until all objects in the set have been joined together. The essence of the analysis lies in choosing the appropriate measure of association and in determining what values should be used to represent each variable for the "clustered" objects. A thorough discussion of cluster analysis techniques is presented by Sneath and Sokal (1973).

The specific methods used in the study reported were initially designed to develop a conceptual classification of Connecticut River Valley landscapes (Palmer and Zube 1976). By that method, the environments to be clustered are simulated by photographic representations. The variable characterizing a particular environment is its judged similarity to each of the other environments. Similarity values are determined by the frequency with which a particular environment is sorted by the respondents into the same pile with each of the other environments.

In cases where all ten respondents sorted two particular photographs together, it is assumed that the photographs represent essentially the same conceptual trail environment. It is necessary to retain only one of these scenes in the subsequent analysis. A similarity matrix can be constructed indicating the frequency with which each unique scene is categorized with every other scene. The data in this similarity matrix are used for the cluster analysis.

RESULTS AND DISCUSSION

Seven distinct types of trail environments were identified by the cluster analysis: rural towns, countryside, vistas, pathways, logging activity, trailside features, and backwoods. This classification might be construed as the "average" sorting formed by the "average" respondent. A characterization of each type of trail environment was obtained through content analysis of the descriptive words and phrases used by respondents to describe their categorizations. Both environmental characteristics and activities described for each category were noted. The most frequently mentioned characteristics and activities for each trail environment type are summarized in table 1.

Conceptual Analysis of Trail Types

Rural towns.--These environments all share features indicating a dominant human presence in the natural environment. Roads, especially when paved, play a particularly important role in the identification of this type. One respondent notes "these environments are for tires, not feet; they make dull walking, both hard and tiring." Residential, commercial, and industrial land uses also characterize this type of environment. This environment was frequently separated into subtypes according to intensity of development. For instance, one respondent formed two distinct piles of rural town environments. He described one as "light rural-character development, trails or dirt roads passing homes, secondary roads, and agriculture." The other he characterized as "moderate to heavy development, from residential to major roads; and little evidence of the natural environment."

While it was generally recognized important services are provided in these environments, the universal opinion was they should be eschewed. "Walk faster and take bigger steps" was one person's reaction. "A real down; it is too much like real life at home."

Countryside.--A wide variety of environments revealed a human presence but were still considered to be appropriate to a hiking experience. Among the countryside type of environments, the most commonly mentioned land uses

Table 1.--Characteristics and activities most frequently used to describe each trail type

Trail type	Rank	Characteristic	Rank	Activity
Rural Towns	1	Human dominance	1	Hurry by
	2	Roads	2	Buy supplies, information
	3	Residential, homes	3	Rest, snack, get warm
	4	Commercial, resort	4	Conflict with cars
Countryside	1	Farmland, open fields	1	Camping, campfire
	2	Lean-tos, camps	2	Change from woods, relief
	3	Water, lake stream	3	Walk fast
	4	Powerlines	4	Eat, drink, rest
	5	Human dominance, overuse	5	Socialize, interest in people
	6	Litter, trash		
Vistas	1	Vista, view	1	Gape, photography
	2	Natural, forested	2	Solitude, peak experience
	3	Ridgetops, high peaks		
Pathways	1	Trail, obvious path	1	Hike through, plod, see trail ahead
	2	Woods, natural	2	Wet boots, circumvent obstacles
	3	Wet, muddy, ways to cross muck	3	Chat, socialize
	4	Excessive wear, erosion, disrepair	4	Study wildlife and vegetation
Logging	1	Logging, timbering	1	Annoyed, ugly, unpleasant
Activity	2	Down trees, slash	2	Hard walking
Trailside	1	Edges, open space	1	Visual enjoyment, expectation
Features	2	Water, streams	2	Rest, eat, drink
	3	Unique things, birch stand	3	Reorient, check progress
	4	Signs	4	Study wildlife, bird watching
			5	Camp
Backwoods	1	Natural, forest	1	Boredom, unable to see
	2	Low visibility, no path	2	Study wildlife, explore
	3	Stone walls, stones, rocks	3	Walk on through
	4	Down trees, logging	4	Hard walking, way-looking
	5	Trail, path		

were agriculture, power line rights-of-way, and bodies of water.

The distinction between the countryside environment and rural towns is not complete. Considerable disagreement existed about whether certain photographs were more similar to the rural town environment or to the countryside. As described by one respondent, countryside environments are "usually encountered coming into or out of towns and near road crossings," and further "woods or country (unpaved) roads are often a pleasant break from deep woods trails and offer a different quality which is usually enjoyable."

Countryside environments play a critical role in the success of a New England backpacking experience. Such environments provide an opportunity for "hikers to pause and enjoy a change from monotonous woods; they might even explore the barn or rest on the bridge encountered along the trail." Another aspect of the countryside environment concerns the more rustic "resting places for the weary hiker which offer a chance to mingle with your fellow hikers, have a campfire, eat, and just plain enjoy the outdoors." The lean-tos and other shelters are apparently appreciated by some but not by others.

Vistas.--Each respondent separated vistas from all other trail environments. These photos depicted sweeping overlooks from ridgetops or high points. They offered a "possibility of real solitude at last and a feeling of personal pride

for having made it," and they enabled one to see the "relationship of the landscape's parts." "You stop, you look, you remember it and think," was one respondent's comment. In the words of another respondent, "high places are often the highlight of a hiker's effort; I feel that looking out over wild areas is more enjoyable than looking out over farm areas although views of these areas can be informative." In any case, vistas provided an opportunity to stop and rest, to eat lunch or pitch camp, and most certainly to take a look around.

Logging activity.--This special condition was clearly identified by half the respondents. To some it included "signs of human technology or specifically timber cutting operations." They felt "such reminders of human incursions into the environment are not pleasant" and wished "economic activity didn't intrude." Another respondent recognized the presence of "logging activity" and realized although "probably most don't like it, I don't mind if it is done right and I find it a good use of resources and a 'natural' activity for people in the environment." On the other hand, some respondents failed to realize logging was taking place and only saw "fallen trees, scrub brush," and "slash." In either case this environment was characterized as "mostly ugly." In response to these conditions they envisioned "walking fast and being annoyed" in part because of the unpleasant scene, but also because "down vegetation makes hiking harder."

Pathways.--In every case respondents formed special piles for "obvious paths through the woods." There was unanimous agreement on what to do when one encountered a path--"Hike!"

Trailside features.--Embedded within the general fabric of the backwoods and pathway environments are features that become important to the hiking experience. One respondent describes them as "unique natural features: open water, a birch stand, a low area which is a major change from the trail's ridge character, or a unique geological formation." It is unlikely that such features need be unique. Rather, they are simply "important changes" from the surrounding trail environments.

Trail features also include way markers serving as places to "stop, look, and listen for information so as not to get lost." One respondent considered these environments as a chance to "check on progress and reorient" oneself.

Backwoods.--By far the most common type of trail environment is simply backwoods. This was not unexpected since the New England landscape is 70 percent forested. As described by one respondent, "typical views, quiet and restful, no sun, cool, no water, and not much wildlife" characterize these environments. As noted by another, the "primary activity would be to notice and study different vegetative species. Few other elements can be seen since they are obstructed by understory growth and vegetation. Any experience would be introspective since one could not relate to any more than a very enclosed environment."

Conceptual Relationships Among Types

The hierarchical nature of the cluster analysis routine used made it useful as a descriptive technique. Specifically, the analysis allowed comparison of relationships between clusters at various levels. Hierarchical relationships can be portrayed as a tree diagram (fig. 1).

After the initial seven trail-environment type clusters are distinguished, the next clustering of types results in four classes. The rural town and countryside types join to form a cluster, perhaps representing "developed landscapes" or areas obviously under human dominance. It is notable that vistas retained their separate identity at this level of generality,

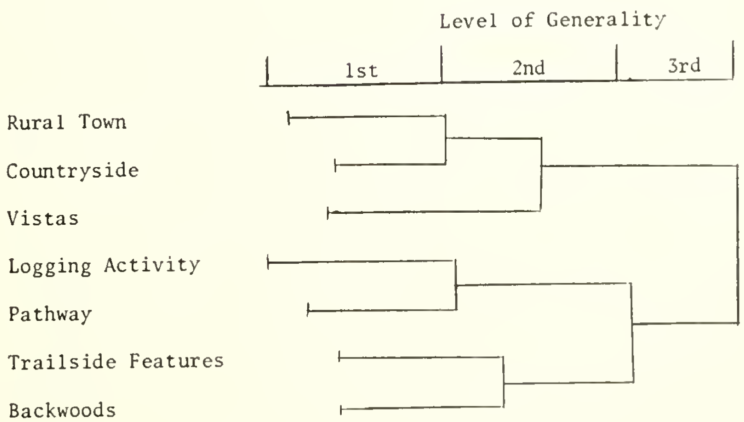

Figure 1.--Tree diagram showing relationships between clusters at three levels.

suggesting that vistas form a more distinct and cohesive category. Logging activities and pathways were joined, probably indicating two different manifestations of human impact within the backwoods environment. Trailside features and backwoods were joined as the fourth class. They seem to be natural environments without any significant human presence.

At the next level the trail environment types are divided into two general classes. One seems to emphasize more natural and the other more human or artificial landscapes. Vistas were joined with rural town and countryside environments to form the class of more human environments. The remaining four types form the group of more natural environments.

Geographic Analysis of Trail Types

One aspect of the sampling strategy employed to inventory the Appalachian Trail for this study involves taking photographs at half-hour intervals of hiking time. This photographic sample can be treated essentially as a random representation of potential scenes experienced on a hike through the study area.

Based on this sample, a reasonable estimate can be made of the frequency with which a hiker might encounter each environment type when hiking through any given area. For example, inspection of table 2 shows that approximately 10 percent of hiking time on the trail is through

Table 2.--The distribution of trail environment types[a]

Environment	Frequency	Percent
Rural town	13	7.0
Countryside	7	3.8
Vistas	4	2.1
Logging activity		
Pathway	7	3.8
Trailside features	3	1.6
Backwoods	151	81.2
Unknown[b]	1	.5
Total	186	100.0

[a]These figures are calculated from a systematic sample of randomly photographed scenes taken from the Appalachian Trail in Massachesetts.

[b]This photograph was sampled but not printed. Therefore, it could not be included among the sorted photographs.

developed landscapes. Vistas were a relatively rare phenomenon (2%); possibly they are more special because of their rarity. On the other hand, an overwhelming percentage (81) of a hiker's time is spent passing through undifferentiated backwoods.

The approximate geographic location of each sample in the physiographic inventory can be determined. Further, each photograph can be categorized as an instance of one or another of the seven trail environments identified by the cluster analysis. Therefore, a "map" can be prepared to represent the sequence of conceptual trail-environment types present on a given trail. Figure 2 is an example of such a conceptual "map."

The map portrays the geographic relationships among the various types of environments encountered along the Appalachian Trail in Massachusetts.

In the southern section (Connecticut to Jug End) the most obvious characteristic is the relative lack of backwoods environments. The forest cover is not very dense, and the trail is generally routed along the edge of ridges, affording prolonged exposure to panoramic views. All of the vistas recorded in the photographic sample occur in this section of the trail.

The next section of the trail leads north across the Housatonic River Valley to the Mass Pike Crossing. The presence of agricultural and industrial development indicated by the map probably underestimates the proportion actually found in this area. This is probably due to the tendency of trail managers to favor wooded routes.

Between the Mass Pike and Dalton the trail passes entirely through backwoods environments. No vistas and few other environment types interrupt this stretch of densely wooded area.

The last section of the trail in Massachesetts is popularly considered the most desirable for hiking; it is also the most developed. The trail passes through three towns that are generally consistent with the character of this part of New England. The popularity of this section is indicated by the heavy representation of pathway types. Vistas do occur in this section of the trail, but they are not present in the photosample. This is because the vistas are as fleeting as they are dramatic. This knowlege makes it apparent that the subjectively sampled component of the trail inventory also has an important contribution to make.

CONCLUSION

The procedures developed and illustrated in this study provide one method for obtaining a conceptual classification of trail environments. The results suggest that these environmental types may be influential in determining where and

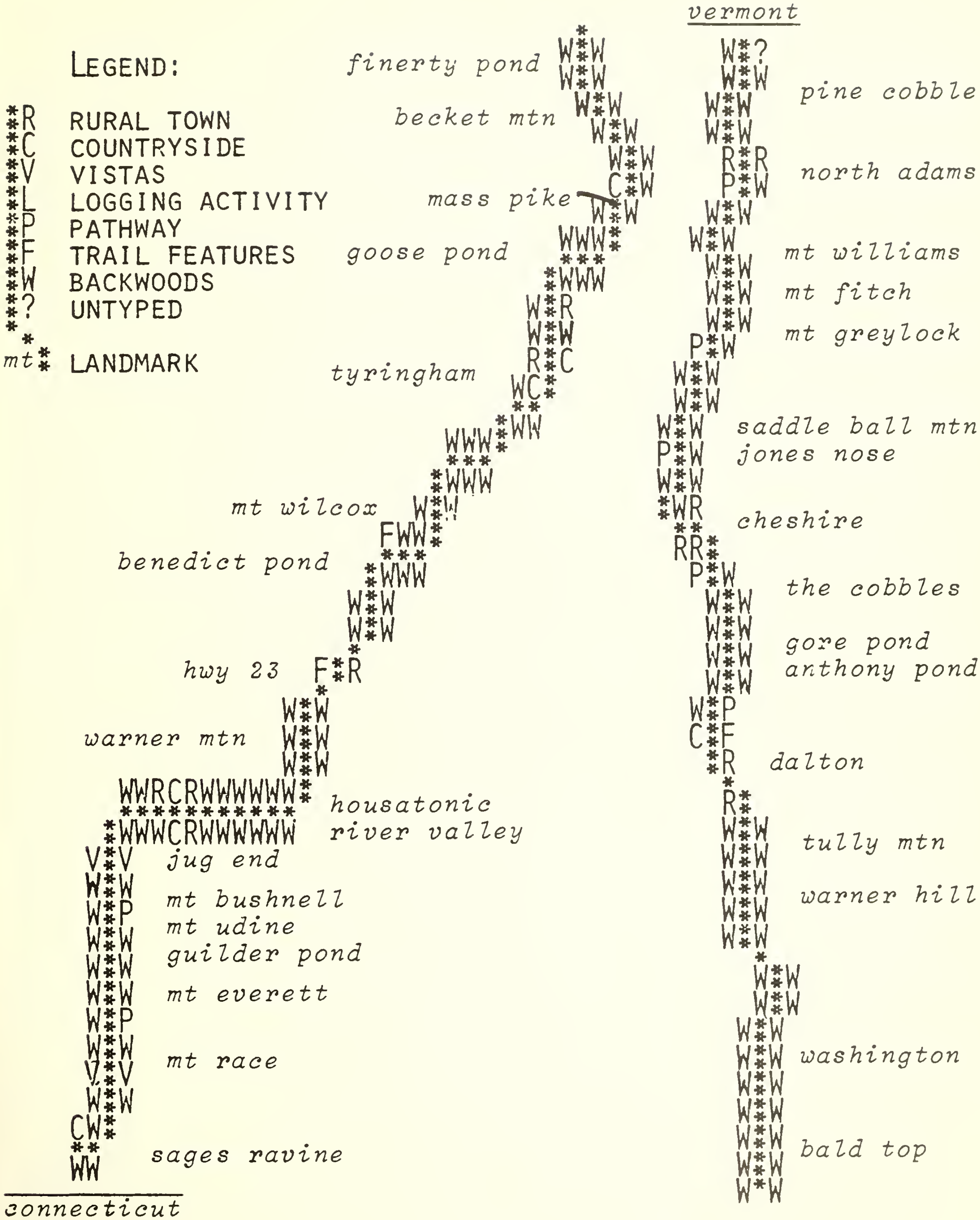

Figure 2.--Conceptual chart of trail environment types.

when various trail activities will occur. The systematic sampling procedure used in this study makes it possible to estimate the relative extent of each trail environment type, as well as its relation to the other types encountered. As the user demand grows for outdoor recreation resources, planners and managers will be particularly in need of methods which provide a generalized geographic inventory of the resource from the point of view of hikers' experiences.

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SOME DISPERSED RECREATION EXPERIENCES AND THE RESOURCE SETTINGS IN WHICH THEY OCCUR[1]

Glenn E. Haas, Deborah J. Allen, and Michael J. Manfredo[2]

INTRODUCTION

This paper reports some results from a program of research which is attempting to quantify the reasons why people engage in different outdoor recreation activities[3]. That research has been designed to develop and apply psychometric instruments for identifying and quantifying the psychological outcomes of outdoor recreation participation. These outcomes define the types of satisfaction (preferred or perceived benefits) realized from specific recreation opportunities.

In this paper a brief overview of the conceptual foundation and methods of the research is followed by some results from three studies of wilderness and backcountry recreationists in Colorado. The paper closes with a short discussion of the relevance of the research to recreation resource management. Brief attention is devoted to other studies completed recently or now in progress.

CONCEPTUAL FOUNDATION

Recreation management can be viewed as a production process, with the services produced traditionally referred to as activity opportunities such as hiking, camping, skiing, and fishing. The emerging behavioral approach to recreation management goes further and defines the primary output of that management as satisfying recreation experience opportunities (Driver and Brown 1975). Under this behavioral approach, which guided the research reported in this paper, recreation experiences are further defined in terms of a group of specific psychological outcomes (Driver and Brown 1978). These outcomes have been previously referred to in the literature as a "package of experiences" (Driver and Tocher 1970) and as "multiple satisfactions" (Hendee 1974).

Based upon this behavioral perspective of recreation mangement, Driver and Brown (1978) have conceptualized a "recreation opportunity demand hierarchy" reflecting four types of recreation demand. These demands are for (1) recreation activities, (2) setting attributes, (3) psychological outcomes, and (4) subsequent benefits. Activity opportunities refer to easily identifiable recreation pursuits such as fishing, swimming, and camping. Setting attributes include those of the physical, social, and managerial environment. Physical resource attributes include such features as rugged topography, water, fish, wildlife, and meadows. Social attributes include numbers and kinds of people encountered, litter, and noise. Managerial attributes include entrance fees, information systems, permits, and other tools and techniques of management. Psychological outcomes include opportunities for being together as a family, being with friends, enjoying nature, getting exercise, risk taking, self testing, and realizing a change from everyday life. Subsequent benefits involve both later individual and societal benefits. For example, individuals might improve their mental health, work performance, or family solidarity by engaging in recreation activities. In turn, society might benefit by having a healthier, happier, and more productive population.

The purpose of the studies reported here was to define the users' recreation experiences in terms of psychological outcomes and to identify preferred physical resource attributes of the recreation settings. Particular attention in this paper is directed toward the fish and wildlife resource attributes.

STUDY AREAS

The three Colorado study areas are the Rawah Wilderness, the Flat Tops Wilderness, and

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1/ Paper presented at a workshop on the esthetic value of wildlife at the Ninth Annual Meeting of the Environmental Design Research Association, University of Arizona, Tucson. April 11, 1978.

2/ The authors are Research Associates, Department of Recreation Resources, Colorado State University, Fort Collins.

3/ The research was supported by the McIntire-Stennis Forestry Research Program at Colorado State University and by the Rocky Mountain Forest and Range Experiment Station, USDA Forest Service. That research was supervised by Perry J. Brown and B. L. Driver.

Indian Peaks backcountry area. (Approximately 70,000 acres of the Indian Peaks backcountry area became a part of the National Wilderness Preservation System in September, 1978.) The Rawah Wilderness is a 27,000-acre area 1-1/2 hours driving time west of Fort Collins; the Flat Tops Wilderness is a 235,000-acre area 4 hours driving time west of Denver; and the Indian Peaks backcountry is a 100,000-acre area less than a 1-hour driving time west of Denver and Boulder.

METHODOLOGY

The field methods involved structured and unstructured interviews and observations. Structured interviews took place at trailheads and along roads as people were leaving a study area. These interviews were conducted to collect visitor use information for area managers (activities by zones, number of people per party, major activity participated in, length of participation) and to solicit names and addresses of users for a more detailed questionnaire. All responses were voluntary. Unstructured interviews were conducted on-site by participant observers who talked with users about the high and low points of their trip, their motives for visiting the area, and their perceptions of the area. Observations were also made of user characteristics and behavior.

Shortly after the end of the summer field seasons a mail questionnaire was sent to a subsample of the users who had provided their names and addresses. That questionnaire solicited information on the users' preferences for specific types of psychological outcomes and physical resource attributes. The basic question asked was, how much did each of the outcome or attribute items listed in the questionnaire either add to or detract from the respondent's recreation experience? Respondents rated each item on a nine-point response format which ranged from most strongly added (coded 1) to most strongly detracted (coded 9). In addition, selected socioeconomic and demographic information was obtained. Responses to the items on the mailback questionnaire were analyzed using the BC-TRY cluster analysis system (Tryon and Bailey 1970). Cluster analysis permitted the empirical development of outcome domains composed of items logically related to the same theme or value. Individual outcome items can be grouped into scales (sub-domains) and the scales can be combined to form domains. In this research items and domains were considered.

RESULTS

Less than 1 percent of the users contacted at each study location refused to voluntarily provide their names and addresses. The number of returned questionnaires (and response rate) for the 1975 Rawah study was 264 (88%); the 1976 Indian Peaks study was 286 (73%); the 1976 Flat Tops study was 222 (85%). The 1975 Rawah study focused on identifying several psychological outcomes. Eight psychological outcome domains were hypothesized and subsequently empirically identified. The 1976 Indian Peaks study focused only on the three setting attributes described earlier. Nine physical resource attribute domains were hypothesized and subsequently empirically identified. The 1976 Flat Tops study dealt with both psychological outcomes and resource attributes. The eight psychological outcome domains and nine resource attribute domains identified in the previous studies were used in the Flat Tops study, but only seven psychological outcomes and eight resource attributes were reliably identified. From this discrepancy, it might be inferred that one psychological outcome domain and one resource attribute domain were either not relevant to Flat Tops users or that the items in the domains need further refinement. In subsequent studies, acceptable reliability coefficients have been obtained for the "escape pressures" domain by further scale refinement.

Psychological Outcomes

The empirically identified and reliable psychological outcome domains are listed in table 1 along with their mean values, a verbal description of the extent to which they were perceived to contribute to satisfaction, and their alpha reliability coefficients. The "escape pressures" domain had a very low reliability coefficient in the Flat Tops study and was omitted as a psychological outcome domain in that study. The remaining domains all had alpha reliability coefficients above 0.60, which was deemed acceptable.

The rank ordered mean responses to the outcome domains were similar for the two areas. "Relationships with nature" was scored as strongly adding to satisfaction by users of both areas. In the Rawah study, "escape pressures" was also scored as strongly adding to satisfaction. "Achievement," "autonomy," and "reflection on personal values" were scored as moderately adding to satisfaction of users in both areas. "Recollection/sharing" moderately added to satisfaction of Rawah users and only slightly added to satisfaction of Flat Tops users. "Risk taking" and "meeting/observing other people" were scored as neutral, neither adding to nor detracting from satisfaction of users in both areas.

Physical Setting Attributes

The empirically identified and reliable setting attribute domains are listed in table 2 along with their mean values, a verbal description of the extent to which they were perceived to contribute to satisfaction, and their alpha reliability coefficients. The "nuisances" domain had a very low reliability coefficient in the Flat Tops study and was omitted as a setting attribute domain in that study. The remaining domains all had alpha reliability coefficients above 0.60, which was deemed acceptable.

Table 1.--Psychological outcome domains identified for 1975 Rawah Wilderness users and 1976 Flat Tops Wilderness users

Psychological outcome domains	Study area: Rawah Wilderness		Study area: Flat Tops Wilderness	
	Mean[a]	Verbal description	Mean[a]	Verbal description
Relationships with nature 0.87/0.89[b]	1.9	Strongly added	1.9	Strongly added
Escape pressures 0.79/	2.1	Strongly added	c	c
Achievement 0.91/0.81	2.5	Moderately added	2.8	Moderately added
Autonomy 0.83/0.78	2.6	Moderately added	2.7	Moderately added
Reflection on personal values 0.84/0.82	2.9	Moderately added	3.1	Moderately added
Recollection/sharing 0.80/0.82	3.1	Moderately added	3.6	Slightly added
Risk taking 0.81/0.69	4.9	Neither added nor detracted	4.9	Neither added nor detracted
Meeting/observing other people 0.83/0.86	4.9	Neither added nor detracted	5.1	Neither added nor detracted

[a]Means were computed from responses to a response format on which most strongly added was coded 1 and most strongly detracted was coded 9.

[b]Reliability coefficients for the domains in the Rawah and Flat Tops studies, respectively.

[c]The escape pressures outcome domain was not reliably identified in the Flat Tops Wilderness study.

The major similarities in the two studies were (1) the same three setting attribute domains were perceived as contributing the most to satisfaction, (2) the "dense vegetation," "rugged topography," and "unique natural feature" domains had virtually identical means, and (3) "man-made intrusions" detracted from satisfaction. The major dissimilarities were (1) the Flat Tops users placed greater importance on the wildlife and fish-related physical resource attribute domains than did the Indian Peaks users, and (2) the Flat Tops users reported that man-made intrusions reduced their satisfaction more than was reported by Indian Peaks users.

Table 3 gives the means of the "fish-related" and "wildlife" physical resource attribute items for the Indian Peaks and Flat Tops studies. These items were perceived either to add strongly or moderately to the user's recreation satisfaction.

Indian Peaks users indicated that "wildlife" contributed more positively to their recreation experience than did the "fish-related" item. The overall mean for the "wildlife" domain was 2.4 (strongly added to satisfaction) while the mean for the "fish-related" domain was 3.2 (moderately added to satisfaction). The Flat Tops users scored items in both domains similarly and more positively than did the Indian Peaks users. The overall mean for the "wildlife" domain was 1.8 while the mean for the "fish related" domain was 2.0 (both strongly added to satisfaction).

Table 2.--Setting attribute domains identified for 1976 Indian Peaks users and 1976 Flat Tops Wilderness users

Resource attribute domains	Indian Peaks Backcountry		Flat Tops Wilderness	
	Mean[a]	Verbal description	Mean[a]	Verbal description
Meadows/forest 0.83/0.90[b]	1.9	Strongly added	1.6	Strongly added
Water-related 0.85/0.87	2.1	Strongly added	1.7	Strongly added
Wildlife 0.89/0.92	2.5	Strongly added	1.8	Strongly added
Dense vegetation 0.79/0.83	2.6	Moderately added	2.7	Moderately added
Rugged topography 0.93/0.94	2.7	Moderately added	2.7	Moderately added
Unique natural features 0.92/0.93	2.9	Moderately added	2.7	Moderately added
Fish-related 0.93/0.87	3.2	Moderately added	2.0	Strongly added
Nuisances 0.77/	5.4	Neither added nor detracted	c	c
Man-made intrusions 0.77/0.69	5.8	Slightly detracted	7.0	Moderately detracted

(Study area spans both column groups.)

[a]Means were computed from responses to a response format on which most strongly added was coded 1 and most strongly detracted was coded 9.

[b]Reliability coefficients for the domains in the Indian Peaks and Flat Tops Wilderness studies, respectively.

[c]The nuisances resource attribute domain was not reliably identified in Flat Tops Wilderness study.

That the "wildlife" and "fish-related" domains were perceived more important to the Flat Tops Wilderness users might be attributed to differences in user and area characteristics. Many of the Indian Peaks visitors live in the Denver metropolitan area, visit the area with their families as day-users, and participate in activities such as hiking, walking, auto driving, and fishing. Visitors to the Flat Tops Wilderness, in comparison, are less often accompanied by children and participate in activities such as hiking, backcountry camping, fishing, and photography.

The differences in wildlife and fish attribute scores might be explained by user expectations for each area. Wildlife and fish are much more abundant in the Flat Tops Wilderness. It is widely recognized for its quality fishing and big game resource.

CONCLUSIONS

Several inferences can be made from the studies reported. First, preferred recreation experiences can be defined by specific psychological

Table 3.--Means of the fish and wildlife resource attribute items for 1976 Indian Peaks backcountry users and 1976 Flat Tops Wilderness users

Resource attribute domains	Study area			
	Indian Peaks Backcountry		Flat Tops Wilderness	
	Item	Mean[a]	Item	Mean[a]
Fish-related	Brown trout	3.27	Brown trout	2.09
	Cutthroat trout	3.33	Cutthroat trout	1.69
	Brook trout	3.01	Brook trout	1.82
	Rainbow trout	3.11	Rainbow trout	2.00
	Grayling	3.19	Grayling	2.61
	Slow moving streams with deep holes	2.99	Slow moving streams with deep holes	1.98
	Naturally reproducing fish populations	3.04	Naturally reproducing fish populations	1.75
	Stocked fish	3.69		
Wildlife	Ptarmigan	2.56	Ptarmigan	1.98
	Grouse	2.71	Grouse	1.98
	Song birds	2.29	Song birds	1.82
	Predatory birds	2.50	Predatory birds	1.88
	Small furbearers	2.49	Small furbearers	2.00
	Squirrels	2.70	Squirrels	2.19
	Elk	2.34	Elk	1.40
	Mule deer	2.57	Mule deer	1.70
	Big horn sheep	2.20	Big horn sheep	1.57

[a]Means were computed from responses to a response format on which most strongly added was coded 1 and most strongly detracted was coded 9.

outcomes. Second, preferences for these outcomes can vary among the recreationists visiting an area. For example, the "relationships with nature" outcome domain contributed more to user satisfaction than did the "risk taking" and "meeting/observing other people" outcome domains in both the Rawah and Flat Tops studies.

Third, the preference by Rawah and Flat Tops users was nearly the same for several outcome domains. Means for "relationships with nature," "autonomy," "risk taking," and "meeting/observing other people" differed by less than 0.2, suggesting that there might be some substitutability among different areas in providing the same kinds of satisfaction.

Fourth, the previous inferences apply to setting attributes. That is, these results suggest that (1) settings can be identified; (2) preferences for these settings can vary among the recreationists visiting an area; and (3) preferences for several setting attributes can be the same across areas.

This type of research has numerous recreation planning and management implications. It aids in defining the preferred outputs of recreation management (recreation experience opportunities). It also aids in identifying the recreational settings preferred by recreationists. Planners and managers can use this information in resource inventory and classification, resource allocation, development of management objectives, selection of management tools and techniques, and evaluation and modification of the recreation system.

Cooperative backcountry and wilderness research has continued between Colorado State University and Rocky Mountain Station to validate the empirically identified psychological outcomes and setting attributes, to identify other outcomes and resource attributes of value to people, to identify types of people demanding specific psychological outcomes, and to relate these specific outcomes to attributes of the physical, social, and managerial setting. Study areas have included the Weminuche, Eagles Nest, and Rawah Wildernesses in Colorado (USDA FS); the Arkansas

River Canyon in Colorado (BLM); the Little Sahara recreation area in Utah (BLM), the Oak Creek Canyon recreation complex in Arizona (USDA FS); and the Popo Agie Primitive Area and Fitzpatrick Wilderness in Wyoming (USDA FS).

A major activity for the next few years will be participating in management-research demonstration projects. One such project is underway for the Maroon Bells-Snowmass Wilderness and its contiguous backcountry between Aspen and Crested Butte, Colo. That project is designed to test the relevancy and applicability of inventory and planning information and tools developed by the research program described in this paper in an actual planning and management situation.

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CURRENT RESEARCH ON ESTHETIC VALUES OF WILDLIFE[1]

William W. Shaw[2]

The principle directions of research on perceived values of wildlife have been and continue to be largely framed by immediate needs of wildlife resource managers. Traditionally, most wildlife management has been oriented toward producing harvestable surpluses of game species, and most socio-psychological research has involved the principle benefactors of this management--sport hunters. The studies of hunters are too numerous to list. Hendee and Potter (1976) summarized 33, and there have been several since that time. Most of these studies have produced basic socio-demographic descriptive information, although a growing number have dealt with perception, motivation, and other behavioral information.

In recent years, however, it has become apparent that sportsmen are no longer the only major interest group actively concerned with wildlife management policies. Memberships in animal oriented organizations of all types ranging from groups which actively oppose hunting to general conservation groups has burgeoned (Witter 1976). Sales of birdseed have risen 5 - 10 percent annually since 1960 (Wildlife Management Institute 1975) and as many as 20 percent of American households feed wild birds (Payne and DeGraaf 1975). A recent national survey estimated that over 49 million Americans participated in some form of wildlife observation in 1976 (United States Department of Interior 1975). These studies are part of the growing body of evidence indicating nonhunting values of wildlife are very significant for many Americans.

These developments have profound implications for the wildlife manager, who typically works within governmental agencies and is charged with managing a resource which by law is publicly owned. One of the most pressing needs. is for an understanding of such basic questions as: Who, in addition to hunters, cares about wildlife? What segments of the public are concerned? How much do they care? About what aspects of wildlife management are they concerned? What kinds of financial mechanisms would they support to supplement the revenue for wildlife management which presently comes primarily from hunters? All of these are pressing questions which must be dealt with if resource managers are to serve the best interests of the public.

This paper will trace a sequence of studies attempting to answer some of these questions. The author will then discuss some observations regarding the state of our knowledge about perceptions of wildlife and directions for future research.

CRITICS OF WILDLIFE MANAGEMENT

Understanding the critics as well as supporters of existing management policies is crucial for management agencies which must deal with public pressure groups. One recent study compared the backgrounds and beliefs of members of three wildlife interest groups: Michigan deer hunters, Michigan Audubon Society members (a group which neither supports nor opposes hunting), and Michigan supporters of the Fund for Animals, Inc. (a nationally prominent, antihunting organization). Using a survey technique, a variety of differences were revealed among these three groups (Shaw 1975, 1977). However, related to the issue of perceived values of wildlife, the similarities between these groups were more significant than the contrasts. In spite of basic philosophical differences between hunting advocates and hunting opponents there was very close agreement on the questions dealing with values of wildlife and threats to wildlife (tables 1 and 2). Since this study, several others have produced similar results (Arthur et al. 1977, Shaw et al. 1978, Witter 1978). Whenever wildlife enthusiasts have been studied, regardless of their sentiments on the volatile issue of hunting, esthetic, and existence values have been rated as the most important values of wildlife and loss of habitat as the most significant threat to wildlife.

Results from these studies suggest two important things for resource managers. First of all, opposition to hunting appears not to be simply an artifact of biological misunderstanding which might be eliminated through effective information and education programs. On the contrary, this sentiment often has deep-seated philosophical origins largely outside the realm of influence of wildlife managers. Consequently,

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1/ Paper presented at a workshop on the esthetic value of wildlife at the ninth annual meeting of the Environmental Design Research Association, University of Arizona, Tucson. April 11, 1978.

2/ The author is Assistant Professor, School of Renewable Natural Resources, University of Arizona, Tucson.

Table 1.--Group means and rankings for reasons wildlife are considered important

Scale: 1 = "extremely important"
5 = "not important"

Reasons	Group means (and ranks)		
	Hunters	Audobon	Fund for Animals
They are part of the ecological balance upon which we are all dependent.	1.60(2)	1.17(1)	1.15(1)
People enjoy viewing wildlife	1.53(1)	1.67(2)	1.63(2)
People enjoy just knowing that they exist.	2.01(3)	2.09(3)	1.70(3)
They are of scientific value.	2.31(5)	2.31(4)	3.10(6)
They play an important part in our cultural heritage (songs, legends, etc.)	2.57(6)	2.54(5)	2.49(4)
They provide hunting recreation.	2.14(4)	3.79(7)	4.85(9)
They help the economy by attracting tourism.	2.72(8)	3.20(6)	3.71(7)
They are a source of food and furs.	2.59(7)	3.80(8)	4.61(8)
Animals may have souls like humans.	3.61(9)	4.04(9)	2.66(5)

Table 2.--Group means and rankings for threats to wildlife

Scale: 1 = "extremely serious"
5 = "not serious"

Threats	Group means (and ranks)		
	Hunters	Audubon	Fund for animals
Loss of habitat due to human developments	1.16(1)	1.22(1)	1.14(1)
Pollution	1.71(2)	1.38(2)	1.32(3)
Illegal hunting	2.12(3)	1.96(4)	1.31(2)
All terrain vehicles (snowmobiles, jeeps, etc.)	3.14(5)	1.92(3)	1.76(6)
Unsound wildlife management practices	2.34(4)	2.30(5)	1.52(5)
Commercial trapping	3.20(6)	2.83(6)	1.41(4)
Legal sport hunting	4.39(8)	3.54(7)	1.89(7)
Predation by other animals	4.31(7)	4.56(8)	4.33(8)

the efforts of wildlife professionals concerned with maintaining and building public support for their activities would be best spent in emphasizing areas in which their activities benefit all types of wildlife enthusiasts, whether hunters or not. Secondly, these results suggest a basis for cooperation among disparate wildlife interest groups on certain very critical wildlife management issues. Although opposed to hunting for philosophical reasons, the members of this anti-hunting group did not see hunting as a major threat to wildlife. Furthermore, the proponents of hunting appear to be largely in agreement with hunting opponents and other wildlife enthusiasts concerning the major values of wildlife.

NONHUNTING WILDLIFE ENTHUSIASTS

If there is a large and perhaps growing segment of the public that is very concerned with the welfare of wildlife but does not hunt, who are they? Our understanding of the feelings of the general public concerning wildlife is still very limited with only a few national studies having looked at these issues (Kellert 1976, 1978; Arthur et al. 1977; Shaw et al. 1978).

One initial approach to understanding how nonhunting wildlife enthusiasts value wildlife is to study those individuals who actively engage in nonconsumptive wildlife pursuits such as bird-watching. Admittedly this is a very specific group and does not include many people who may care about wildlife but do not actively attempt to view wildlife as a primary recreational pursuit. It is, however, a logical starting point because these are people who are directly affected by wildlife management policies.

To do this, 591 wildlife enthusiasts visiting selected prominent bird watching sites in southeastern Arizona were surveyed in 1977 (Shaw et al. 1978; Witter et al. 1978). This study provided a basic socio-demographic description of nonhunting wildlife enthusiasts visiting these sites. In addition, a number of items dealing with perceptions of wildlife values and wildlife management priorities were included. As in other studies of wildlife interest groups, esthetic and existence values of wildlife were more important than other possible wildlife values to these individuals (table 3). In general, they felt that wildlife management presently benefits mostly hunters and that wildlife management priorities

Table 3.--Values of wildlife rated by 591 visitors to selected bird watching sites in southeastern Arizona

Scale: 0 = not valuable at all to you personally
10 = extremely valuable to you personally

How valuable is it that wildlife...	Mean value
1. Are factors in nature's balance	9.5
2. Are indicators of environmental health of the world	8.8
3. Teach people about nature	8.7
4. Help maintain the human bond with nature	8.7
5. Are simply existing in the wild	8.5
6. Are sources of excitement in life	8.1
7. Are reasons to get out-of-doors for awhile	8.0
8. Are reasons to get-away-from-it-all for awhile	8.0
9. Are spiritually uplifting	7.8
10. Are photographic subjects	6.6
11. Are subjects to be sighted and listed in a wildlife diary	6.5
12. Bring people together in fellowship	6.2
13. Are subjects for scientific study	6.0
14. Are sources of stories to tell others	5.4
15. Are subjects for art work	4.9
16. Are subjects for medical research	3.1
17. Are subjects for viewing in zoos	3.0
18. Are feather sources (goose and duck down)	1.6
19. Are meat sources	1.0
20. Are subjects to be hunted	0.8
21. Are pets	0.7
22. Are circus performers	0.7
23. Are fur and leather sources	0.5
24. Are raw materials for fashion industry	0.2
25. Are trophy sources (antlers, head, or body mounts)	0.2

favor hunting interests over nonconsumptive interests. Interestingly, although these people do not actively support wildlife management agencies, they do not actively oppose them. They tend to see hunting as a legitimate activity and wildlife management as primarily oriented toward serving these interests. In summary, they are basically nonaligned on the hunting issue and prefer to support private wildlife conservation organizations rather then governmental agencies. Importantly, these people are very much in favor of any proposals to promote cooperation between hunting and nonhunting concerns in the interest of wildlife welfare.

These individuals, who actively pursue nonconsumptive uses of wildlife, place a very high esthetic value on wildlife and behave accordingly. Over 50 percent indicated that wildlife appreciation was their most enjoyable outdoor recreational activity, and 79 percent listed it as one of their three most enjoyable activities. They considered wildlife habitat preservation as a top concern among environmental issues and environmental quality as a top concern among broad social issues (health care, national defense, etc.). These findings were supported in a related study that compared the beliefs and attitudes of members from three national organizations: Ducks Unlimited, Inc. (hunters), The Wildlife Society (professional wildlife managers), and American Birding Association (avid birdwatchers) (Witter 1978).

Active nonhunting wildlife enthusiasts are individuals who care a great deal about wildlife and perceive wildlife esthetics as a major aspect of their lives. And yet, these are individuals whose concerns and activities are almost entirely outside the domain of most wildlife management that occurs within public resource management agencies. In order to serve the best interest of the entire public and enlist the broadest possible support for wildlife conservation agencies, it behooves natural resource managers to attempt to understand and work with these nonhunting wildlife enthusiasts.

FUTURE RESEARCH NEEDS

In many ways, research on the esthetic values of wildlife is only beginning. More[3] conducted a comprehensive review of the literature dealing with nonconsumptive uses of wildlife and concluded research is in a transition between asking "how much" and "who participates." There exists a need to go beyond the role of describing individuals in a traditional socio-demographic sense and study motivations and perceptions relating to wildlife appreciation.

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Sampling designs need to be improved so inferences can be drawn beyond the actual study populations. Detailed studies of the general public and its perceptions of wildlife are needed although some research of this nature is currently underway. Much can be done and needs to be done to refine and improve methodologies for studying wildlife esthetic values, and the validity of these methods needs to be examined by using different methodologies and examining behavioral correlates with research findings. Shaw and King[4] have one attempt currently underway to measure values of wildlife using two basically different approaches. One is the sociopsychological approach using self-reported importance scales, memberships in wildlife organizations, wildlife-related recreational pursuits, etc. as measures of importance. The second is an economic approach based on human allocation of resources (time and money, etc.) for wildlife appreciation. The validity of various techniques for assessing esthetic values can be determined by simultaneously using several different approaches.

Considerable progress has been made in developing techniques for measuring landscape and forest esthetics, and some of these methods may be applicable to studies of wildlife esthetics. Particularly valuable are some of the rigorous experimental designs used in these areas of esthetic research. Researchers would be well advised, however, to recognize certain unique aspects of wildlife esthetics. Esthetic values entail two basic human domains. One is perception of the stimuli. The second is the cognitive processes whereby we attribute values to the objects or stimuli. In most (if not all) situations, both of these factors are involved. However, in the case of wildlife, the cognitive element appears to be particularly significant. For many people, wildlife are symbolic of environmental quality and man's relationship to nature. Furthermore, a strong tendency to project human feelings or anthropomorphize when thinking about animals undoubtedly influences esthetic perception. Our greatest needs for research on wildlife esthetics are in understanding the complex relationships among experiences, attitudes, and beliefs which intervene between perception of wildlife stimuli and the attribution of esthetic value to wildlife.

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THE ESTHETIC VALUE OF WILDLIFE: PERCEPTIONS OF THE AMERICAN PUBLIC AND SPORTSMEN[1]

Louise M. Arthur[2]

Wildlife management has long been recognized as requiring at least as much effort directed toward the management of people as of wildlife itself (Murie 1954, Bean 1977). Similarly, the goals of wildlife management have been defined in terms of human need, particularly the needs of hunters and fishermen. This focus on sportsmen's needs is at least partially based on their providing the bulk of current revenues for wildlife management, up to 80 percent by some estimates (Hendee and Potter 1975).

Although there has been a shift from the earlier "game bagged" objective of wildlife management to a "man-days afield" one, even the latter objective is directed at the so-called "consumptive" uses of wildlife. Only recently have nonconsumptive values such as ecological, existence, and esthetic values of wildlife begun to receive significant attention. With the recognition of these nonconsumptive values has come recognition of the desires of nonconsumptive users, of nature lovers, bird watchers, and other members of the nonhunting public who may enjoy wildlife if only vicariously.

Some of this increasing attention to the desires of nonsportsmen may stem from financial concerns; if game populations continue to decline, a greater proportion of wildlife management funding will have to be obtained from nonconsumptive sources. The rapid increases in the number of people actively involved in wildlife protection groups (Witter 1977) and the environmental sensitivity of the general public have also contributed to the redefinition of wildlife management objectives to incorporate the expressed interests of both active sportsmen and nonsportsmen.

1/ Paper presented at a workshop on the esthetic value of wildlife at the Ninth Annual Meeting of the Environmental Design Research Association, University of Arizona, Tucson. April 11, 1978.

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The concerns of the vocal environmental interests may not, however, directly represent more general public concerns. Furthermore, the current emphasis of wildlife management on assuring sportsmen some minimal degree of hunting and fishing success may not accurately reflect the desires and perceptions of sportsmen; there are some indications that sportsmen are more interested in experiencing the natural environment, enjoying companionship, and escaping home problems than in bagging a limit of game (Knopf et al. 1973, More 1973, Potter et al. 1973). In order to obtain an accurate indication of the esthetic value of wildlife relative to other values such as hunting pleasure, food, and fur, a series of surveys of American sportsmen and the general public was conducted by the U.S. Fish and Wildlife Service and the U.S. Department of Agriculture. Two of the surveys were extensive telephone surveys of random samples of American households (see Arthur et al. 1977 and U.S. Fish and Wildlife Service 1977). The other two were more intensive and pervasive mail surveys of American hunters and fishermen (U.S. Fish and Wildlife Service 1977) and purchasers of duck stamps.[3]

ATTITUDES OF THE GENERAL PUBLIC

The results of the two surveys of general public perceptions and uses of wildlife indicated a wildlife policy directed toward providing game animals is not consistent with general public interests. In a joint U.S. Department of Agriculture-Fish and Wildlife Service Study conducted in May-June 1976, 2460 respondents (78% response rate) were asked to rate the importance of several aspects of wildlife on a 0-10 scale, where 0 indicated no importance and 10 indicated extreme importance. For the exact wording of this and other items write: Environmental Economic Studies, Economics, Statistics, and Cooperatives Service, Room 420, GHI Building, U.S. Department of Agriculture, Washington, D.C. 20250. The results are shown in the following tabulation:

3/ Arthur, Louise M. 1978. Attitudes toward wildlife management: a study of hunters and fishermen in the U.S. U.S. Fish and Wildl. Rep., in progress.

Importance of various aspects of wildlife.

Aspects	Mean points
Ecological value	8.9
Existence value	8.6
Viewing pleasure	8.3
Food source	4.8
Hunting opportunity	3.8
Fur source	2.5

When respondents were asked to divide 100 points among three aspects--hunting opportunity, existence value, and viewing pleasure--to reflect their relative enjoyment of each, the distinction was dramatic:

Relative enjoyment of three aspects of wildlife.

Aspects	Mean points
Viewing pleasure	52
Existence value	37
Hunting opportunity	10
TOTAL	99

Thus, viewing wildlife (defined as "in person or in pictures") was more important to the respondents than hunting. Furthermore, no significant difference was found between the importance ratings assigned to viewing pleasure by prohunters and anti-hunters ($F=0.41$, $p<0.5$); both groups rated viewing pleasure over 8. Hunting opportunity, on the other hand, received a mean rating of only 5.6 from the 55 percent of the sample which approved of hunting and a rating of 1.8 from anti-hunters.

A 1975 U.S. Fish and Wildlife Service survey of 106,294 households and over 300,000 individuals suggested much of this viewing pleasure is either unplanned or vicariously accrued via printed pictures, television, or movies, for instance. Extrapolations indicated that of 184.3 million Americans over 9 years of age, only 49.3 million took special trips for wildlife observation and only 15 million photographed wildlife. Some 74.5 million hunted or fished. In addition, nearly half of the participants in wildlife observation and more than half of the wildlife photographers were also hunters and fishermen.

ATTITUDES OF HUNTERS AND FISHERMEN

The 1975 U.S. Fish and Wildlife Service mail survey of 3,500 waterfowl hunters again indicated aspects of wildlife experiences other than the killing of game predominate in determining levels of user satisfaction. A cluster analysis of responses to the 1975 Waterfowl Survey revealed only a small proportion of success-oriented hunters (17%). Nevertheless, even 70 percent of this group judged experiencing nature's beauty as more important than bagging a limit. Across all respondents, experiencing the wildlife environment was the most important motive for hunting and the most important factor in the enjoyment of hunting. Almost 90 percent of waterfowl hunters took special trips outside the hunting season to view waterfowl.

Similar motives have been identified in fishermen. Although the 1975 U.S. Fish and Wildlife Service survey of over 20,000 hunters and fishermen did not focus on many of the non-success benefits of hunting and fishing, the responses to warmwater fishing issues listed in the following tabulation suggest that some of the most important aspects of the fishing experience are related to esthetic qualities of the wildlife environment:

Percent selection as one of three most serious threats to the quality of warmwater fishing

Threats	Percent
Water pollution	88.3
Conflict with boats	48.1
Habitat destruction	42.9
Poor land management	36.5
Restricted access	27.1
Too many fishermen	23.4
Illegal fishing	19.6

The exact wording for this and other items are available in Arthur.[3] Knopf et al. (1973) have found fishermen are primarily motivated by desires to experience natural settings, display skills, and escape various personal problems.

CONCLUSIONS

The ratings in the first two tabulations suggest survey respondents valued esthetic aspects of wildlife more than any direct consumptive use. Thus, wildlife management policy designed primarily to enhance hunting opportunity would likely be suboptimal from a public perspective. The intensive surveys of sportsmen's attitudes on various aspects of the total wildlife experience revealed that such a policy might also be suboptimal from the sportsman's point of view. The most important determinant of hunters' and fishermen's satisfactions seemed to be related to experiencing the esthetic aspects of the wildlife environment.

These results[3] suggest that sportsmen would willingly consider trading lower bag limits or creels and higher user fees for the continued opportunity to enjoy a quality wildlife environment. Some of the more obvious ramifications of this willingness to pay a higher per animal cost for external benefits would include the ability to generate additional revenues through increased user fees and the use of these additional revenues for enhancing various aspects of the wildlife

environment other than sizes of or access to wildlife populations.

Sportsmen's interests are, in general, congruent with public interests. Both are concerned with protecting wildlife habitats and providing wildlife sanctuaries, not for the sole purpose of assuring supplies of game for hunters, but, for instance, to assure the existence of various species, to introduce species into new regions, and to provide viewing pleasure. Even when success could be more easily assured, as through the stocking of fish, factors of wildlife management dealing with the environment surrounding wildlife experiences were judged more important than success.[3]

Thus, wildlife resources may not be measured properly in terms of hunting and fishing success rates, days afield, or perhaps even number of animals or species. More important is insuring the quality of the natural habitats of wildlife, providing quality experiences for man in these habitat environments, protecting wildlife so people will know they are being protected, and providing ample visual opportunities for naturalistic and vicarious observers. For instance, crowding was considered a major detraction from quality wildlife experiences, with the exception of warmwater fishing.[3] The importance of management for esthetic, nonconsumptive goals will likely continue to increase with the decline in hunter success (Stankey et al. 1973), the growth in urbanization (Kennedy 1973), and the increase in environmental sensitivity of the public.

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THE USE OF SURVEY INSTRUMENTS IN DETERMINING THE ECONOMIC VALUE OF ENVIRONMENTAL GOODS: AN ASSESSMENT[1]

David S. Brookshire

Thomas D. Crocker[2]

INTRODUCTION

Historically, the esthetic effects of pollution and landscape alteration have been given little attention in economists' efforts in quantitative policy analysis because they have been treated as intangibles. That is, by definition, esthetic attributes are incorporeal and awkward to define and formulate. Strictly interpreted, an intangible thing cannot be measured because no objective unit of measurement is known to exist or no acceptable method of measurement is available.

The application of economic analysis to esthetic phenomena offends many people. Even some economists are willing to argue that some kinds of pleasure and pain are perhaps best kept separate from the mean-minded activities of the marketplace (Bensusan-Butt 1974). Nevertheless, it is important to recognize that while the integrated body of analysis which constitutes economics should not be the only means for evaluating institutional or technological adaptations, or developing assessment methods for the social aspirations that cause esthetic and environmental insults, it does have its place. The economic treatment of environmental and esthetic issues as mere choices among human expedients views man as the "measure of all things." Thus, pollution damage to human health and happiness are really more "economic" than is damage to property. The latter is simply an intermediate means to health and happiness.

There exist philosophical views of the esthetic consistent with the application of economic analysis to esthetic phenomena. Consider the following statements of Berndtson (1969):

". . .beauty is an object of value, a process of evaluation, and a seizing in immediate enjoyment of what is valued in that process." (p. 185)

Beauty thus illustrates an ideal of human experience: the act of valuation is competent to its task; the object valued is apprehended immediately rather than through surrogates; and the object valued is owned and enjoyed in the act of valuing it." (p. 185-186)

Esthetic experiences, then, involve a decision process differing from other decision processes only in that the valuation act and the enjoyment of the object are coincidental and immediate. If the form of the valuation procedure is independent of the enjoyment of the object, there is no reason in principle why standard economic-analytic techniques of valuation cannot be applied to esthetic phenomena. Economic analysis presumes, as does the above philosophical perspective, that beauty and its value lie in the eye of the beholder. Beauty, or esthetic phenomena, given some physical measure in accord with human senses, should in principle be no more unmeasurable in economic terms than the price of cabbage in a supermarket. No laws whatsoever governing economic activity are innate in the material objects of ordinary cognition. Economic laws relate to the subjective desires that motivate individuals to alter the facts of their environment. Thus no object becomes relevant in economic analysis until humans perceive it can be used for some subjective purpose.

Many material objects and services that provide esthetic experiences have public good attributes. There are no observable market prices for these goods and services from which to infer individual behavior and valuations. Survey instruments obtaining information about the manner in which individuals behave when confronted with these experiences as well as the values they attach to them must therefore usually be adopted as the means of acquiring the necessary data.

Recently a host of efforts in the valuation of environmental goods have been attempted. These efforts are termed contingent claims

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mechanisms. Within the overall approach, there are direct and indirect techniques. The first is termed the bidding game approach and the second the substitution game approach. A bidding game elicits information necessary for the estimation of a Bradford bid curve (Bradford 1970). The survey instrument is a structured device that draws upon routinized and institutionalized settings to elicit bids. A substitution game elicits information necessary for the estimation of a household production function. The survey instrument elicits activity time, expenditure, and location information. The output of the estimation process is a compensated demand curve for the good being valued. See Blank et al. (1977) for a discussion of the model and estimation process. A wide variety of environmental goods has had these techniques applied in a valuation procedure. Randall et al. (1974) and Blank et al. (1977) attempted to value visibility changes in the Four Corners Region of the Southwest. Brookshire et al. (1976) addressed the problem of potential visibility reduction in the Glen Canyon National Recreation Area resulting from the proposed Kaiparowits coal-fired power plant. Thayer and Schulze (1977) attempted to value the lost esthetic value in the Jemez Mountains, New Mexico, resulting from geothermal development. The problem of esthetic effects of strip mining in Appalachia was addressed by Randall et al. (1977). Brookshire and Randall et al. (1977) applied the bidding and substitution game techniques to valuing wildlife resources in the Rocky Mountain Region.

The magnitude of the valuation results obtained from studies employing contingent claims mechanisms has been surprisingly large. For the Brookshire et al. (1976) study the average bid per family or recreator group was $2.77 in additional entrance fees per day in 1974 dollars. The total annual bid, which can be interpreted as an aggregate marginal willingness to pay to prevent one additional power plant near Lake Powell, was over $700,000. If one were to extrapolate to the 15 national parks and recreation areas within a 100-mile radius of the proposed Kaiparowitz site, the aggregate bid would approach $20 million per year.

The Blank et al. (1977) experiment resulted in an extrapolated annual estimate for visibility reduction in the Farmington, N. Mex. area of $916,000 for the Navajo Reservoir. This is roughly consistent with the Glen Canyon National Recreation Area results.

Finally, the Brookshire et al. (1977) wildlife valuation experiment produced an estimated valuation of $72 per year to increase expected elk encounters from 0 to 5 per day of hunting. This is consistent with fees charged by private clubs ranging from $85 to $150 per year.

The value estimates in the above results are quite large, but economists thoroughly distrust the results because of the methodologies used.

All of these studies have required application of survey instruments. While contingent valuation approaches are soundly grounded in economic theory, a major point of contention among economists has been the use of survey instruments for gathering data. The following statement by Fromm (1968) exemplifies the attitude: "Furthermore, it is well known that surveys that ask hypothetical questions rarely enjoy accurate responses." (p. 174) A lengthy discussion of the use of questionnaires in the paper on which the Fromm (1968) effort is a commentary is summarily dismissed with this single unsupported statement. See Blank et al. (1977), Brookshire et al. (1977) for the development of the theoretical underpinnings of the contingent claims mechanism. An additional area of concern has been whether individuals exhibit strategic behavior when responding to survey instruments. Strategic behavior by individuals is exhibited when the respondent is presented with an incentive structure in a survey instrument and then attempts to influence the outcome. Subsumed in this is the notion of the free-rider problem on which economists have produced volumes of literature. The problem of strategic behavior has been viewed as one of the major impediments to the valuation of environmental goods. See Brookshire et al. (1976), Blank et al. (1977), Brookshire et al. (1977) and Thayer and Schulze (1977) for the lack of empirical evidence for strategic behavior. In spite of practically no empirical evidence to support the existence of strategic behavior by individuals when responding to a questionnaire about environmental and esthetic phenomena, economists have expended enormous intellectual energies in devising ways to cause individuals to reveal their behavior and their preferences truthfully when responding to questions about these and other nonmarketed goods. Originally set forth in "A New Principle of Just Taxation" by K. Wicksell (Musgrave and Peacock 1967) in 1869, the public goods preference revelation problem was rediscovered by Samuelson (1955). The first reasonably complete preference revelation device is in Clarke (1971). Smith (1977) provides an up-to-date review of the problem and its suggested solutions. Perhaps because they are complex, few, if any, of these devices have found their way into actual survey instrument construction. Nevertheless, the volume of papers devoted to the issue of obtaining accurate revelations of preferences for nonmarketed goods gives weight to any assertion that economists distrust empirical results based on data generated by questionnaires.

The purpose of this paper is not to debate the reality of strategic behavior. Instead, the intent is to raise the possibility economists, by their near-exclusive devotion to the strategic behavior problem, have neglected many of the analytical and empirical advantages gained through the use of survey instruments.

NEED SURVEY INSTRUMENTS BE HYPOTHETICAL

Fromm (1968) and many other economists believe hypothetical questions generate inaccurate

answers. These inaccuracies, if one judges by the relative emphasis in the literature, are caused by an incentive to give untruthful answers. The incentive stems from the advantages the individual perceives would accrue to him if he behaves strategically. Presumably one knows the answers are untruthful because the individual's observed behavior and the preferences this behavior reveals are often not consistent with the individual's statements about his preferences. If one believes hypothetical statements are imaginary (fictional), then he would hardly be surprised by these discrepancies. Another interpretation is possible, however.

The dictionary defines a hypothetical proposition as a conditional proposition (i.e., an "if x, then y" statement). A hypothetical question would then be a conditional statement in the subjunctive mood, an "if x were. . ., then. . .?" statement. In a survey setting, the hypothetical question is posed by the interviewer to the respondent; the respondent then states how he intends to behave in the posited situation. Thus, the respondent might be shown a number of pictures of different landscapes and be asked his expectations about his budget and/or time allocations for each of the depicted landscapes.

Formally, the problem set before the respondent seems no different than the problem faced when planning on the basis of a weather forecast to spend an afternoon at a picnic. The respondent's realized activities and planned activities are neither instantaneous nor coincidental. An updated forecast altering the type of weather expected, may change the respondents' plans to spend only enough time at the picnic to eat lunch. Realizing that meteorology is an inexact and conditional science, the respondent will, if it is not too comsumptive of energy, be prepared to change plans again on receipt of new information.

It would be surprising if frequent discrepancies did not occur between responses to hypothetical questions and subsequently observed behavior. A contingent answer is acceptable given the well defined circumstances presented to the respondent. The question of inaccuracy is not whether given a change in circumstances the observable behavior pattern changes but whether the contingent answer can be observed when the defined circumstances have not changed. Only if the answers relate to past rather than intended behavior will a simple comparison of answers with actual behavior suffice to ascertain the accuracy of the answers. Otherwise, one must explain how the individual responds to new information and circumstances in order to perform the comparison.

Even if the previous argument is accepted, the question remains as to how contingency answers fit into the consumer's surplus framework. This framework provides the analytical engine by which economists attach values to nonmarketed goods.

Assuming for simplicity that the questionnaire respondents' demand for an activity is weakly complementary in the nonmarketed good of interest, it is easy to illustrate the relation between hypothetical environmental or esthetic states and consumer's surplus. According to Maler (1974, pp. 183-189), weak complementarity exists if the quantity demanded of a private good or activity is zero when the marginal utility of the public good is zero. The condition permits one to avoid having to solve for utility and expenditure functions when trying to establish the demand for a public good by exploiting its connections with private, marketed goods. In figure 1, participation in the activity with which the nonmarketed good is associated is assumed to have an invariant opportunity cost of p. This opportunity cost is independent of the level of availability of the nonmarketed good. The $\bar{D}$ curve in figure 1 gives the individual's income-compensated demand function for an activity, A, averaged over all possible levels of the nonmarketed good. For example, A might be a fishing activity and the nonmarketed good might be atmospheric visibility.

The ability to see distant mountains from the fishing location is assumed to enhance the utility of the fishing activity. As shown in the figure, the efficient plan for the individual with no forecast of the availability of the nonmarketed good is to look forward to undertaking the activity at level a_0. Activity level a_0 is assumed to represent a day with average visibility versus clear or murky. At this level, the marginal value attached to an additional planned unit of the activity just equals his opportunity cost. The consumer surplus expected from the activity once actually participated in is the area above the opportunity cost line and beneath the demand function. In short, the area under the "average demand" function, $\bar{D}$, is the individual's mathematical expectation of the valuation attached to the planned activity levels, once realized.

Now suppose the individual receives additional information about the availability of the nonmarketed good. Again for simplicity, assume that the additional information will indicate whether the atmosphere will be clear, C, or murky, M, on the day planned for undertaking the fishing activity. The manner in which the angler will revise the estimates about the probability of clear or murky conditions can be described by Bayes' (1764) rule. A good elementary presentation of Bayes' (1764) rule is available in Raiffa (1970, pp. 17-21). For instance, if the improved information predicts clear atmospheric conditions, the angler's subjective evaluation of the average compensated demand function will be $\bar{D}/C$. The level of the activity then planned to be undertaken will increase to a_0^C. Moreover, the area, b-d-e-f, gives the increase in expected utility if "clear" is the forecast of atmospheric visibility. Similarly, if the forecast states "murky," the angler's expected utility level will be reduced to a_0^M, and the area, b-d-h-g, gives the loss in expected utility due to the forecast.

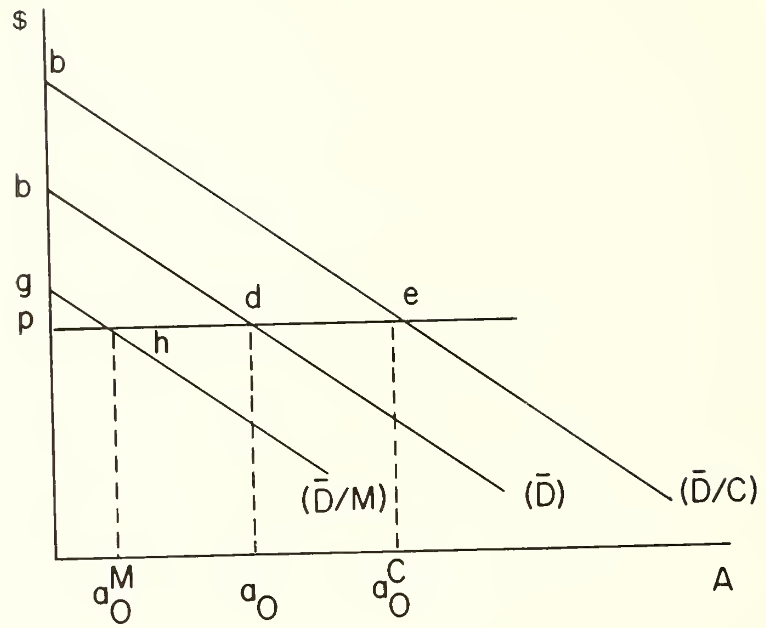

Figure 1.--Effect of an improvement in information on Consumer's Surplus.

In essence the consumer surplus an individual expects to obtain from the availability of a nonmarketed good can be extremely sensitive to the state of information about this availability. This expectation determines the commitment of resources and time--behavior. Adaptive behavior, once having committed one's self and experiencing unanticipated regret or satisfaction thereby, can be treated as the acquisition of further information. Customary treatments of consumer surplus refer to the surplus an individual obtained from participating in an activity, given (implicitly) the state of information at the instant of the actual participation decision. The information at this instant need not be complete. When dealing with a hypothetical situation, the consumer surplus measure refers to the value the individual expects to obtain. This decision is dependent on the state of information about the availability of the public good at the time the hypothetical decision is made. Obtained surplus refers to the surplus associated with $\bar{D}$; the anticipated surplus refers to surpluses associated with demand functions similar to $\bar{D}/C$ and $\bar{D}/M$. Expectations can, in principle, be equally disappointed or fulfilled with $\bar{D}$ as with $\bar{D}/C$ or $\bar{D}/M$. The substance of consumer surplus is not at all altered by increasing the possibility of information acquisition. The dismissal of the use of questionnaires because of their hypothetical nature seems little more than insisting reality conform to analytical habit and convenience.

SURVEY INSTRUMENTS AND BENEFIT-COST ANALYSIS

By attributing discrepancies between stated and realized choices solely to strategic behavior, economists, as the preceding section argues, may have often misconstrued the meaning of data acquired by survey techniques. In addition to strategic behavior and acquisition of information, there is another and potentially more important reason for these discrepancies. For nonmarketed goods, the hypothetical world circumstances posited in instruments differ from the circumstances in the world of observable behavior. This is the essence of the difference between questionnaires and instruments. The mechanisms currently employed for valuing nonmarket goods must, by definition, posit a contingent world representing a different level of the environmental good. In this section, we will argue that the circumstances in the world of instruments correspond closely to the analytical foundations of benefit-cost analysis. That is, data gathered by survey instruments may often, for nonmarketed goods, be more consistent with economic theory than is data generated by observable, realized behavior.

The employment of benefit-cost analysis is an attempt to ascertain the quantity of some numeraire (e.g., current dollars) the gainers and losers from some proposed public investment will

consider equivalent in value to their respective gains and losses. The price structure, where price is a sufficient measure of social as well as private value, represents the terms in which the world is evaluated. Prices, as generated by market exchange and adjusted in proportion to excess demand, embody all relevant information about relative economic scarcities and are a sufficient means of allocating resources to their socially most highly valued uses. Benefit-cost analysis is an attempt to ascertain what individuals are willing to pay and/or would have to be paid for the public investment in a world where markets are pervasive.

If realized market behavior is used as the data base for establishing these valuations, the analyst uses propositions from economic theory for two purposes: (1) to infer what the price structure would be in a world of pervasive markets; and (2) to reason from the pervasive market price structure to the implied consumer valuations. When survey instrument responses are employed for the data base, the first step can be avoided, provided the conditions posited in the instrument correspond to a world of pervasive markets. One might reasonably question whether the conditions corresponding to a world of pervasive markets are sufficiently close to a respondent's experiences to be meaningful. This justifiable doubt must be weighed, however, against the difficulties of carrying through the analytical exercises necessary to construct a pervasive market price structure from initial knowledge of the price structures of a world where markets for many goods are not pervasive. The way in which this difficulty is customarily avoided when using observable, realized prices is to assume that the observed prices correspond to those in a world of pervasive markets.

It is relatively easy to construct examples to make apparent the difficulties of reasoning to pervasive markets from observations on nonpervasive markets. Consider costs of exchange, a phenomenon present whenever valuable resources (e.g., time, information, legal and police services, etc.) must be expended to perform the exchange process.

In figure 2 the individual's initial endowment of Y_1. and Y_2 is at Q. When exchange processes become costly, the individual's budget constraint will vary according to initial endowment. This is because the costs of the act of exchanging Y_1 for Y_2 differ from the costs of exchanging Y_2 for Y_1. Thus, from the perspective of a single individual, the cost of engaging in a transaction in which an automobile owner by the individual is to be exchanged for clean air may differ from these same costs in a transaction where clean air is exchanged for automobiles. Thus, if the exchange act is costly, an initial endowment of Q implies a budget constraint of VQV, whereas if the exchange act is costless, the budget constraint is MM, the customary form which is an integral part of derivations of demand functions and their associated consumer surpluses. When the individual completes the exchanges during the period, Y_1^0 and Y_2^0 will be selected as an optimum if MM is operative. If VQV is the operative budget constraint, Y_1' and Y_2' will be selected. If some point on MM other than Q constitutes the initial endowment, costly

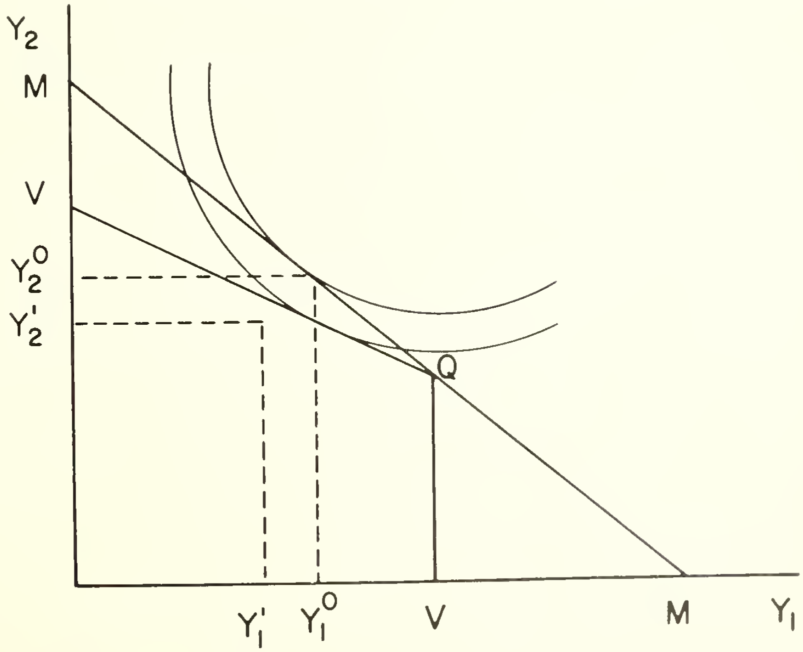

Figure 2.--Effect of Costly Exchange.

acts of exchange will mean a budget constraint different from either VQV or MM may be operative because the costs of exchange acts may differ by the relative quantities of the goods in the initial endowment as well as by types of goods. Thus, the individual budget constraint may vary according to the form in which the initial endowment was accumulated, although the market value of this endowment may be identical for many combinations of Y_1 and Y_2. Since costs of the exchange act differ according to the original Y_1, Y_2 combination, each combination will result in a different and generally nonlinear budget constraint. From this it follows from the individual's perspective, a dollar is not an explicit, invariant pecuniary measure. Instead, the subjective value of an additional dollar depends on the form of the income change (i.e., on the good in which the increment is embodied). Moreover, it appears realized market behavior is dependent not only on money incomes and relative market prices of goods, but also upon the combination of goods the individual starts with and the relative and absolute costs of exchange associated with those goods. These costs of exchange acts are probably neither trivial nor similar across individuals.

The huge sums spent on industries (law, middlemen, etc.) whose major or sole purpose is to facilitate exchanges attests to their importance. In addition, if exchange act inputs, including native intelligence and training, are not distributed equally across the population, and if these inputs contribute positively to the effectiveness of an individual in producing exchanges, then costs of exchange acts will not be similar across individuals.

If realized market behavior depends on the costs of the exchange act for the bundle of goods an individual holds, if for the same bundle of goods these costs differ across individuals, and if individuals do not hold similar goods bundles, then the analytical effort required to infer what the price structure would be in a world of pervasive markets must clearly be greater (probably much greater) than when all individuals have no exchange act costs. Therefore, budget constraints are invariant with respect to the bundle of goods held. Rather than facing these and similar analytical complexities directly in order to construct the price structure of a world of pervasive markets, it may often be more effective to question the individual about his responses where he is to assume that markets are pervasive. That is, the individual is allowed to respond directly to a perturbation in a world of pervasive markets rather than having the investigator try to infer what the individual would do in a world of this sort from information about a world where markets are not pervasive.

An individual may be able to state preferences for a particular state of the world quite clearly. However, if markets are nonexistent or incomplete (as they in fact are for a great many esthetic and environmental goods), there may be no means to communicate these preferences. The very lack of markets is due to the costs of forming and maintaining them and the costs of the act of exchange. In a survey instrument a hypothetical (contingent) world can be constructed in which costless means of communication are available. On occasion, therefore, the individual's preferences are perhaps more readily inferred from statements rather than from behavior. The individual who drives a 1965 Plymouth Valiant and states a preference "for" clean air has no market in which to directly exchange the old heap for some clean air.

CAN SURVEY INSTRUMENTS REDUCE A PRIORI ASSUMPTIONS?

The ability of the human mind to cope with complex reality is limited. Successful grappling requires that the dimensionality of reality be reduced. When trying to establish the collection of values individuals place upon nonmarketed goods, there are at least two general ways to drastically reduce the number of parameters that must be estimated. First, one can draw upon a priori restrictions from the economic theory of the consumer. Second, one can adopt an experimental approach to the question of data.

Economists who have ever seriously worked with problems of consumer analysis are thoroughly familiar with three fruitful a priori restrictions (additivity, homogeneity, and symmetry) that come from the neoclassical demand theory of Shutsky (1915) and Hicks (1934). Further reductions in dimensionality of the parameter space in which estimation is to be carried out can be achieved by judicious invocation of various separability conditions. Perhaps the best overall review of the state of demand theory from the perspective of the development of a priori restrictions to assist in estimation problems is Goldberger (1967). Finally, recent developments in the application of mathematical duality principles to consumer theory allow one to reduce the number of parameters to be estimated without imposing particular monotonicity and curvature properties upon the consumer's maximization problem. Diewert (1974) reviews the applications of duality theory to economic problems.

The second general class of means of reducing the parameter space includes experimental as well as questionnaire techniques. These techniques are advantageous, even though widely neglected in economics, because they permit the investigator to control the number and levels of different physical contexts and adaptation opportunities to which the individual must respond. The setting is one in which disturbances imposed by confounding variables upon the responses of interest are partially controlled for in the data generating exercise. This contrasts with the standard practice of placing sole reliance in an ex post fashion upon the application of multivariate parametric estimation techniques. For

a given number of observations, questionnaires increase degrees of freedom and the efficiency of estimators.

The use of experimental and survey techniques to reduce the parameter space may not be advantageous only on statistical grounds. Often, as noted earlier, the investigator imposes ex post various separability conditions upon market-generated data in order to make it more tractable. These separability conditions may imply, for example, that beer drinking at the local tavern is not a substitute for cross-country skiing. The conditions are imposed without consulting the individuals whose responses are registered in the market data. They are instead generated by what the investigator intuitively feels to be "reasonable," and what is required for analytical convenience. It is by no means clear that the investigator's "feelings" and the framework used in accounting for what is and what is not important is to be preferred to actually providing the respondent with the opportunity to give a response to contingencies. The details to be abstracted from are presented to the respondent rather than being left to the mind of the investigator. In both situations, simplifications are made to permit the investigator to work with the data. In the survey instrument case, however, the respondent gets the opportunity to weigh the importance of these confounding variables to the choices. In the observed behavior case, the investigator is presuming to know as well as the respondent what, from the respondent's perspective, is and is not an irrelevant alternative. Survey instruments allow the domain in which the response data is generated to conform to the structures of the underlying analytical model rather than forcing, via a set of possibly tenuous assumptions (e.g., the absence of jointness, the presence of perfect competition, etc.), the real-world-generated data to conform to the preconceptions of the model.

A slightly different facet of the above point arises with the recognition that much market data used by economists for empirical analysis is collected by agents who are often untrained and usually many times removed from the economist-user. Often, this data is collected as by-products of the activities of organizations whose interests are far removed from and possibly much less disinterested than the research economist. The old saw about lying with statistics can just as readily refer to the manner in which data are organized for presentation as to the manner in which already organized data are employed for estimation purposes. Except possibly in the case of direct investigator observation of market responses, the generation of response data via survey instruments or experimental means can make the specific connection between the reporting of data and its uses for testing hypotheses strong and certain. The investigator then has no choice but to accept the responsibility for the questionnaire data generated. He must accept ultimate responsibility for the origin of the data, as well as the analytical model and the estimation procedures used to test hypotheses.

SURVEY INSTRUMENTS AND PROPERTY RIGHT STRUCTURES

Market prices act as devices to signal and coordinate the purchases and activities of disparate individuals. For example, the spot exchange of two currencies requires no statement of the terms other than the exchange ratio. When cardinally measurable and homogeneous commodities such as currencies are exchanged, the parties to the enterprise need only count the quantities exchanged to establish what they have obtained.

In valuing environmental goods, there are two issues at hand. First, given an existing property right structure, what is the value? Second, what would be the value of the environmental good if the property right assignments underwent a reassignment? The first issue, while important, can be assumed accomplished if the second issue can be answered.

The problem in answering the second issue is that the costs of exchange cannot be assumed to be as trivial as in the exchange ratio example. If one adopts an economic efficiency perspective, then trivial exchanges are not forthcoming due to tracing the parties initially responsible for the environmental or esthetic effect, detailing the actual levels of the effect, and finally ascertaining the contributions of each perpetration of the effect.

When these costs of the act of exchange exist, the economic structure itself becomes a variable of the decision problem. The problem can be viewed as finding a set of obligations for each individual's behavior pattern to make costs and rewards less dependent on joint relations with other individuals using the same non-marketed good. Rules of evidence and procedure are established for all users. Likely and important contingencies will be specified, and appropriate responses will be stipulated. Objective, easily measured performance standards will be formulated. In short, the assignment of property rights as well as the property rights structure itself is changed. These reassignments and restructurings of property rights have been a means by which environmental and esthetic insults have been controlled. It is likely they will continue to be a major means.

There exist analytical devices in economics that allow one to ascertain the effect of property rights reassignments of an environmental or esthetic good upon consumer valuations. If there is an increase in pollution, the amount the sufferer would have to be paid in order to be willing to accept the increase is consistent with the polluter being liable for the damages caused.

The amount the consumer would be willing to pay to prevent the increase implies that the polluter has zero liability for any harm imposed upon the sufferer. These valuations can be established with time and budget allocation data obtained through behavioral observations or by questionnaires. However, where the conditions of use, exclusion, or alienation are altered (i.e., property rights are restructured), there is no everyday behavior to observe, except insofar as one is willing to draw analogies from observed behavioral responses to changes in the property rights structures of other goods. If one knew what the availability of the environmental good would be under the property rights restructuring, it might seem one could, if one had everyday behavioral observations on consumer time and budget allocations at the same level of availability, determine the change in consumer valuation due to the property right restructuring. Furthermore, since consumer valuations will, through either the market or the political process, influence the level of availability, how is one going to reason from the level of availability to consumer valuations for the restructured property right? Thus the only sound way of obtaining an estimate of whether the net benefits of a particular property rights restructuring are positive, if one insists upon employing observed everyday behavior, would be to perform the restructuring and observe the results. To measure is not necessarily to understand. Trial and error can be an extremely costly way to perform research because the errors are real rather than hypothetical. In contrast, survey instruments allow one to investigate the behavioral responses to a wide variety of property rights structures without involving the citizenry in the traumas of social experimentation.

One cannot observe directly everyday behavioral responses to property rights structures that have never existed. Similarly, one cannot observe directly the everyday behavioral responses of individuals who have never participated in activities with which the environmental or esthetic good is associated at the levels at which the good has been historically available. If some of the proposed levels of availability have not been historically available, and if some former nonparticipants would become participants at these new levels, the use of data on observed behavior to ascertain valuations would mean the valuations of the would-be participants play no part in determining the valuation. For each proposed level of availability, the use of observed, realized behavior to establish valuations will mean only historical participants may be counted. Those who have not participated historically have no opportunity to communicate their preferences. Survey instruments, because they allow the researcher to introduce broader than historic ranges of available environmental or esthetic good can allow the values of historical nonparticipants to become relevant. Experience has shown unless this process begins with the current property rights structure, respondents have difficulty in answering. However, this does not prevent the eventual valuation under a new property right structure. See Blank et al. (1977), Brookshire et al. (1977) for these points.

CONCLUSIONS

The preceding is a taxonomic discussion of some reasons why survey instruments may be a superior means of generating data with which to value environmental and esthetic goods. It is argued that economists have erred in viewing the situations they point out as necessarily fictional; that the data generated by survey instruments may, for nonmarketed goods and the activities with which they are associated, accord more closely with the conditions of received economic theory; that survey instruments make it easier to remove the difficulties of estimation and interpretation introduced by confounding variables; and that survey instruments often permit one to more readily deal with phenomena that have not been in the range of historical experience. These are indeed substantial advantages that economists have not recognized or appreciated. However, recognition of the advantages does not cause the disadvantages to disappear.

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USER-BASED ASSESSMENTS OF THE VALUE OF FISH AND WILDLIFE RESOURCES

David A. King[1]

INTRODUCTION

The purpose of this paper is to discuss methods being used in two studies now underway to estimate the demand for and the economic value of a wildlife resource and a trout fishery. The general approach being taken is the application of a modified form of the Hotelling-Clawson model (Clawson and Knetsch 1966; Brown and Nawas 1973; Gum and Martin 1975). The distinguishing methods being used in these studies relate to achieving better measurement of "tastes and preferences" and improved specification of their influence on demand. To noneconomists, the emphasis of this paper may appear to be demand rather than value. However, estimates of value are calculated from estimated demand functions for the environment or resource.

STUDY SITUATIONS

The wildlife appreciation study[2] is being carried out in Cave Creek Canyon of the Chiricahua Mountains of southeastern Arizona.[3] The Canyon is in the Coronado National Forest. Portions of the study area are privately owned, but the major share of the wildlife appreciation activities of visitors occurs on national forest lands.

The major wildlife attraction in the area is the coppery tailed trogon. Bird watching activity in the trogon nesting area is increasing rapidly, causing the USDA Forest Service to institute regulation of the activity.

Because of the private residences and public visitor facilities, hunting is not a major activity in the Canyon proper. The facilities, however, do provide bases from which hunters may carry on their activity.

Visitors to the area are being sampled as they leave it. Wildlife appreciators are identified and a sample of them will be surveyed by mail to gather the data for the study. Wildlife appreciators are identified as those respondents who mention wildlife-related elements in response to an open-end question regarding the attractions of the Canyon and/or mention participation in a wildlife-related activity during their visit.

The trout fishing study is being carried out on the Fort Apache Indian Reservation (also known as the White Mountain Apache Reservation).[4] The tribe sells fishing permits on a daily or annual basis. Their objective is maximization of net revenue. To aid the tribe in developing fee and management strategies, we are studying the structure of demand for trout fishing in the major use area of the Reservation.

Personal interviews of an on-site sample of fishermen are being conducted at 21 fishing sites. A mail survey is also being conducted with a sample of purchasers of fishing permits.

ECONOMIC MODEL

As stated above, the economic model being used is that developed by Clawson (1959) based on a suggestion by Hotelling (1947). Since first applied by Clawson, the approach has been greatly modified, primarily in response to Clawson's own discussions of its shortcomings.

The demand for a good or service is a function of the price of the good or service, prices of substitutes, income, tastes, and preferences. Ignoring, for the moment, tastes and preferences, the specific method being used is that of Sublette and Martin (1975) and also reported by Gum and Martin (1975). In general, it is an individual approach to demand estimation as opposed to the aggregate approach used in most studies employing the Hotelling-Clawson model.

1/ The author is Professor, School of Renewable Natural Resources, University of Arizona, Tucson.

2/ This study is supported by the McIntire-Stennis Forestry Research program at the University of Arizona, project 2016-4168-03 and Wildlife Management Institute, the American Petroleum Institute, and the National Wildlife Federation.

3/ Shaw, William W., and David A. King. 1977. Nonconsumptive uses and values of wildlife at selected locations in southern Arizona. Unpublished research proposal. University of Arizona, School of Renewable Natural Resources.

4/ This research is supported by the Regional Research program of the University of Arizona, project W-133, and the Rocky Mountain Forest and Range Experiment Station, grant agreement 16-736-GR.

In the two studies, trips per individual will be the quantity variable. Price will be represented by the variable costs of participation. Substitution possibilities will be taken into account by measuring the total trips taken for wildlife appreciation to places not in Cave Creek Canyon and total annual expenditures for wildlife appreciation trips, and total fishing trips per year taken to places not on the Reservation. Demand functions within income classes will be estimated as suggested by McConnell (1975).

TASTES AND PREFERENCES

Cross-section analyses are typically used in outdoor recreation demand studies because reliable data time series are not available. In these studies, the potential for variations in preferences among individuals has been recognized as important for some time (King 1968). The typical approach to this problem has been to include socio-economic variables in the demand specifications tested. It was hypothesized these variables could stand as proxies for preferences. In terms of explaining variation in recreational activity, the results have been equivocal or negative (King 1968, Gum and Martin 1977).

Gum and Martin (1977) investigated the structure of demand for outdoor recreation in Arizona. Based on 49 variables, they derived 8 structural dimensions of demand. Using these dimensions, they identified eight types of recreationists and an unclassified group. They concluded for 70 percent of the households in Arizona tastes and preferences were the most important factors influencing outdoor recreation activity.

We have found preference variables derived from a factor analysis of respondent rankings of preference for activities (Richards and King 1977) are better predictors of whether or not a household engaged in an activity than are household characteristics.

In recognition of the importance of preferences, an expansion of the preference-forming process was included as an element in a heuristic model for recreation behavior developed by King and Richards (1977). The model provides the general conceptual underpinnings of the two studies described here.

Wildlife Appreciation Study

This project involves three major objectives: (1) estimation of the importance of wildlife using social-psychological measures; (2) estimation of the economic value of Cave Creek Canyon to the wildlife appreciators using it; and (3) determination of the existence of an association between the social-psychological measures of importance and the estimates of economic value. The social-psychological measures of the importance of wildlife can be considered as proxy measures of tastes and preferences.

The value of an object to an individual may arise from different sources or uses of the object. Hence, how wildlife appreciators rate various sources of wildlife values is being used as one of the measures of importance. In response to the question, "How valuable is it to you that wildlife are?", respondents are asked to rate various sources of value on a 0 to 10 scale. Two example of sources of value are "meat sources" and "subjects for nature study."

Presumably, wildlife appreciators with strong preferences for wildlife appreciation would rate the "nature study" source of value higher than the "meat source" of value.

Actions respondents have taken in support of wildlife conservation are another measure of importance. Included are such actions as joining wildlife organizations, contributing money to support of game and nongame wildlife programs, and lobbying for wildlife conservation programs.

Initial analysis will involve cross-tabulations of responses to identify potential patterns and groupings of responses indicating homogenous sets of respondents with regard to their feelings about the importance of wildlife. Beyond cross-tabulation, V-type cluster analysis will be used to identify one or more dimensions of the general domain of sources of value. V-type cluster analysis identifies items (variables) that scale the same dimension of a domain of interest. It is similar to factor analysis in that it groups variables representing similar structural information. Respondent scores on the scales identified will then be used in O-type cluster analysis to identify homogeneous clusters of respondents. O-type cluster analysis uses the dimensions identified by the V-type cluster analysis. Respondents are scored on the dimensions or scales identified by the V-type analysis and are then clustered based on similar scores on the various dimensions. For a complete presentation of the methods see Tryon and Bailey (1970). Estimates of the recreational experience demand function for each of the clusters will then be made using the Hotelling-Clawson approach.

If statistically significant differences in demand functions are found to exist between clusters of respondents, then this approach to incorporating tastes and preferences can be said to have been empirically successful. And, since the estimates of value will be derived from the demand functions, "better" estimates of value will result from the approach because of the improved specification of the demand functions.

It is important to note this approach is primarily empirical. The conceptual basis is not specifically defined, consisting only of the logic that ratings of sources of value and actions taken in support of wildlife should be associated with the economic values placed on wildlife as evidenced by the economic sacrifices made to engage in wildlife appreciation in the Canyon.

Trout Fishing Study

In this study the preferences are being measured in a more specific way than in the wildlife appreciation study. One instrument being used was developed by Driver.[5] Over a period of several years, Driver has developed a set of scales which measure the preferred psychological outcomes of participation in recreational activities. The theory of expectancy value is the conceptual basis for the scales. The empirical basis is over 30,000 usable responses of recreators in various parts of the United States.

The domains (clusters of associated scales) being tapped for this study are the following: achievement, independence/autonomy, equipment, family togetherness, being with people, learning-discovery, relationships with nature, reflect on personal values, creativity, nostalgia, exercise-physical fitness, escape physical pressures, escaping family, and temperature. Because the conceptual and empirical bases of these scales are well developed, O-type cluster analysis will be used directly to type the fishermen.

Contributions of natural environmental attributes to the satisfaction of the fishermen is being measured with an instrument developed by Brown et al. (1978). The dimensions being tapped are meadow-forest, water-related, wildlife, vegetation, topography, fish-related, nuisances, and intrusions. Attributes regarding man-made recreational facilities have been added for this study.

Examples of the two instruments are shown in figure 1. Part A is from the Driver instrument and Part B from the Brown instrument.

Based on a study of the users of the Flat Tops Wilderness in Colorado (Brown et al. 1978), it appears specific sets of environmental attributes may be related to specific sets of preferred psychological outcomes. Such relationships will be investigated in this study.

If such relationships are found to exist generally, they may provide a means of quantifying the contributions of an environment's attributes to the total value of that environment for a given recreational use. It would then be possible to develop value estimates that can be more readily generalized from area to area than those made from current valuation models.

Provided that sufficient observations are obtained, recreation experience demand functions will be estimated within clusters of respondents defined on the basis of preferred psychological outcomes, environmental attributes, and income.

5/ Driver, B. L. 1977. Item pool for scales designed to quantify the psychological outcomes desired and expected from recreation. Rocky Mtn. For. and Range Exp. Stn., Fort Collins, Colo. (mimeo).

Fishermen vary in their preferences. Things that one fisherman likes are often disliked by another. The questions below give you a chance to let the managers of the White Mountain Recreation Enterprise know about your preferences.

A. Different types of fishing opportunities provide fishermen different types of experiences. This question attempts to identify the types of experiences you desire to realize when fishing on the Fort Apache Indian Reservation. Several types of experiences are listed below. Please do not be bothered by duplication or similarity of some of the experiences, as we need your responses to all of them for greater accuracy.

Rate how much each of them either added to (+) or detracted from (−) the level of satisfaction you received on your last fishing trip to the Reservation. If any of the experiences are not relevant to you, mark the "Not applicable" box. Mark one box for each experience.

	Effect on Your Satisfaction									
	Adds to (+)					Detracts from (−)				
Experiences	Most strongly	Strongly	Moderately	Slightly	Neutral	Slightly	Moderately	Strongly	Most strongly	Not applicable
1. Getting out of doors										
2. Getting away from civilization for awhile										
3. Gaining a sense of self-confidence										
4. Viewing the scenery										
5. Thinking about your personal values										

B. The items below deal with different natural and man-made environmental features which might affect the enjoyment you get from fishing on the Fort Apache Indian Reservation. Please rate each of the following features of fishing sites in terms of how much each of them added to (+) or detracted from (−) the level of satisfaction you received from your last trip to the Reservation. If any of the features are not relevant to you when fishing on the Reservation, mark the "Not applicable" box. Mark only one box for each item.

	Effect on Your Satisfaction									
	Adds to (+)					Detracts from (−)				
Natural Environmental Features	Most strongly	Strongly	Moderately	Slightly	Neutral	Slightly	Moderately	Strongly	Most strongly	Not applicable
1. Clean fresh air										
2. Rainy weather										
3. Wide views of terrain										
4. Presence of mule deer										
5. Large roaring streams										

Figure 1.--The two survey instruments: Driver (A) and Brown (B).

FUTURE WORK

The approaches being taken in these two studies are primarily empirical. Although the scales measuring the preferred psychological outcomes and the contributions to satisfaction of environmental attributes have good conceptual and empirical bases, a specific conceptual link between them and an economic model of consumer behavior has not been made.

New approaches to consumer behavior, referred to variously as household production theory (Becker 1965; Lancaster 1971), hedonic price index theory (Muelbauer 1974), or the new theory of consumer behavior, are being developed

and may provide a framework for linking the social-psychological approaches and the economic approaches to quantifying the demand for the value of outdoor recreation resources. Work will begin soon to try to establish the linkage (King 1977).

The process of preference formation should be addressed (King and Richards 1977). The scales developed by Driver (1977) and Brown et al. (1978) measure the current state of these preferences for an individual. How did the individual come to hold them? If the process of preference formation were understood, then perhaps we might be able to predict changes in preferences over time.

CONCLUSIONS

Economic methods for user-based assessments of the value of natural environments for recreational uses are available. Further research and development of these methods should proceed along two lines to gain understanding of the process of preference formation and to incorporate existing measures of preferences into an economic model of demand and value.

Continuing research from various disciplinary viewpoints is needed to attain an understanding of human perceptions and valuations of natural environments. This understanding is necessary to the achievement of the ultimate goal of developing commensurable measures of the values of natural environments. More cooperation across disciplinary boundaries is needed.

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WHAT BELONGS WHERE: RESEARCH ON FITTINGNESS OF MAN-MADE STRUCTURES IN NATURAL SETTINGS[1]

Joachim F. Wohlwill[2]

Among the concerns of landscape architects and others involved in siting and design of man-made structures in natural settings the achievement of a sense of congruity between such structures and their surroundings has traditionally occupied a primary place. Landscape architects such as Simonds (1961) have stressed the feeling of harmony among the elements of a landscape as a major source of the sense of esthetic pleasure afforded by it, while even earlier Hubbard and Kimball (1929) among others went into great detail on the ways in which the landscape architect might strive towards a sense of fittingness in relating the color, form, and texture of his materials to the natural setting.

The appropriateness and suitability of particular buildings and other works of man in natural settings have likewise been at issue in recent controversies pitting environmentalists and conservationists against developers and commercial and industrial concerns. Consider the frequent battles fought in legislatures, court rooms, and communities over such issues as siting power plants, burying high-voltage transmission lines, constructing highways through parks, establishing recreational complexes such as that at Mineral King in the Sierras, etc. While these controversies clearly revolved around issues of conservation and protection of environmental quality as much as around matters of esthetic appearance, the latter aspect has generally played a prominent part, both explicitly and implicitly in debates between the opposing interests.

In spite of the practical relevance of the problem, little actual research has been carried out on the individual's response to this aspect of congruity or fittingness between man-made and natural elements. There are scattered studies on the determinants of visual intrusiveness of buildings and highways in the landscape (e.g., Steinitz and Way 1969, Hopkinson 1971), along with work by Zube et al. (1974) on the role of visual contrast and land-use diversity and compatibility in judgments of scenic quality. Of particular interest in the work of Zube et al. is the fact that an index of compatibility between adjacent land-uses devised by Hendrix and Fabos (1975) which was utilized in their research was found to be the best predictor of evaluations of perceived landscape quality.

The present investigation extends the above research by following an experimental approach in which specific man-made elements (i.e., buildings) are constructed to represent increasing levels of visual contrast with and obtrusiveness in their natural landscape settings, and presented to subjects for different types of evaluative judgments. The chief response variable in this paper involves direct judgments of the appropriateness of a man-made feature in its natural setting. The expectation was that these judgments would vary inversely with the amount of contrast and obtrusiveness. Esthetic preference, or liking, on the other hand, may be expected to exhibit an inverted-U-shaped relationship to level of contrast, such that preference will be maximal at some intermediate level. This assumption is based on an extension of optimal levels of stimulation notions such as have been advanced by Fiske and Maddi (1961), and in the realm of environmental esthetics more particularly by Berlyne (1967). This optimization function, while repeatedly verified for the variable of complexity, has not been subjected to similar empirical investigation with respect to the dimension of congruity.

A further variable is the nature of the context in which the man-made elements are shown, and specifically the scenic appeal of the context, as well as the amount of man-made development contained in it. Thus, it would be expected the perceiver would make more stringent demands on fittingness or congruence between a man-made object and its natural surroundings in a highly scenic area than would be the case in an area with more ordinary scenery. Similarly, in undeveloped landscapes the function relating contrast to judged appropriateness should display a steeper negative slope than in developed landscapes.

A final variable to be considered is the character and meaning of the man-made objects. Clearly the function attributed to a building will

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[1] Paper presented at the symposium on environmental esthetics at the Ninth Annual Meeting of the Environmental Design Research Association, University of Arizona, Tucson. April 10, 1978.

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be an important determiner of its judged appropriateness in a particular landscape, and this factor is apt to interact with, and possibly even to mask, the role of visual contrast. Accordingly it was hypothesized judgments of appropriateness would decline more sharply with increasing contrast with respect to buildings bearing no essential relation to their landscape than with respect to buildings considered functionally appropriate in their setting.

METHOD

The nature of the proposed research, which called for the presentation to subjects of views of buildings systematically varying in contrast and obtrusiveness in relation to a constant landscape setting, required a method of simulation permitting the construction of stimulus series varying along the dimension just cited, while retaining a maximum of realism and fidelity to some prototypic landscape. To this end, two models of coastal landscapes were devised, and two types of model buildings were constructed in different versions so as to create a five-point scale of varying contrast and obtrusiveness of the building to its setting. The two models, to be designated as "scenic" and "plain," were designed to replicate coastal scenes encountered along the California coast. The scenic model simulated the area around Big Sur, being wooded, hilly, and generally rugged. The plain model was representative of coastal scenes encountered near Santa Barbara and other portions of southern California, being relatively flat and devoid of vegetation except for isolated trees. The "plain" landscape was employed in two different versions, an undeveloped one, (i.e., lacking any man-made features except for the particular building serving as focal stimulus for judgment, which was also true of the "scenic" model), and in a developed version, where the focal building was shown in a context of a variety of other buildings near-by. Thus, the focal stimuli were presented in three different settings: "scenic," "plain-undeveloped," and "plain-developed."

The two types of buildings selected were a "factory," and a "lodge." The former was actually a lumber-mill, and its function was made explicit by a sign, "Pacific Lumber," which was plainly visible in the foreground in one of the three simultaneously exposed views from which the building was presented. The latter was similarly identified by means of a sign, "Ocean Inn." Both the factory and the lodge were presented so as to vary in terms of (a) color and (b) size. The three color schemes employed, from lowest to highest contrast, were brown with dark gray roof, light gray with reddish brown roof, and white with bright red roof. Size was represented in terms of overall size and, in the case of the factory, addition or deletion of appropriate auxiliary structures. The two dimensions were combined into a single five-point dimension of contrast-obtrusiveness. For each version of each building in each setting, three slides were taken from different directions, two facing towards the "sea" (visible in the background) from each side, and the third facing toward the "interior." Black-and-white reproductions of slide-triads illustrating the lodge in the "scenic" setting and the factory in the "plain" setting are shown in figures 1 and 2.

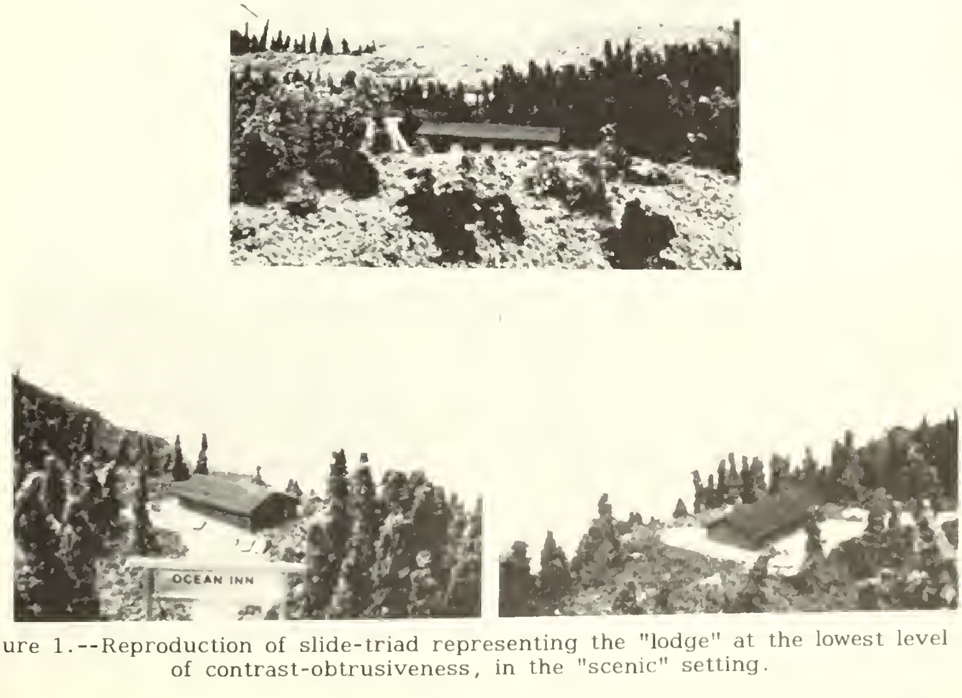

Figure 1.--Reproduction of slide-triad representing the "lodge" at the lowest level of contrast-obtrusiveness, in the "scenic" setting.

Figure 2.--Reproduction of slide-triad representing the "factory at the highest level of contrast-obtrusiveness, in the "plain" setting.

Color slides were taken of the buildings in their settings by means of a camera especially designed for use in conjunction with the Environmental Simulator in the College of Environmental Design at the University of California at Berkeley. In addition to the series of target stimuli already described, a set of "filler" slides was constructed, utilizing a variety of other buildings such as apartment buildings, office buildings, gas stations, etc. photographed in the same scenery models. These pictures were included to avoid the sense of monotony that would result from viewing a series of slides containing only variations on the factory and the lodge themes.

Stimulus series

Each subject viewed a series of 24 slide-triads. The first nine triads contained three stimuli varying only in size, and three varying only in color, along with three filler triads. The remaining 15 contained 5 further filler triads along with 5 triads representing the factory in 1 of the 3 landscape settings in its 5 levels of contrast-obtrusiveness, and the lodge in a different landscape setting, in its 5 levels. Thus, three subgroups of subjects were required: group A viewed the factory in the plain-undeveloped setting and the lodge in the scenic setting; group B viewed the factory in the scenic setting and the lodge in the plain-developed setting; and group C viewed the factory in the plain-developed setting and the lodge in the plain-undeveloped setting.

Subjects

There were two groups of subjects. One (N=42) was drawn from majors in the various departments of the College of Environmental Design at the University of California at Berkeley; their median age was 23.9 years. The other (N=36) was drawn from classes in introductory psychology in the summer school at the California State University at Hayward; their median age was 21.5 years.

Procedure

The experiment was carried out in a small classroom with six to eight students at a time. The general purpose of the study was explained to them (i.e., that we were interested in how people view the appropriateness of different kinds of buildings in natural settings). Subjects were told they would see triads of slides, each triad containing three different views of a particular building in a coastal-zone area. They were to rate the appropriateness of that building to its particular setting, based on its appearance in the three views. They themselves were to be the judges as to the criteria on which this judgment was to be based.

The 7-point rating scale they were to use, printed on their data sheet via rows of numbers from +3 to -3 for each of the 24 items, was explained. Before they made their first rating, each set of subjects viewed for familiarization purposes, a set of 10 slides taken from a series belonging to 1 of the other groups. This procedure gave them an advance notion of the type and variety of stimuli they would be asked to rate and allowed them to establish a frame of reference for the judgments they would be asked to make once their series of 24 items started.

At the conclusion of the session, subjects were asked to fill out an abbreviated version of the author's "civilism-wildernism" scale, adapted from Hendee's "urbanism-wildernism" scale (see Wohlwill and Heft (1977), for details). The scale was intended to assess the students' preference for or against development and the implements of civilization in the context of a vacation trip into a natural recreation area. They were further asked to rate their familiarity with developed and undeveloped portions of the California coast on a seven-point scale.

RESULTS

The main results of the study are shown in two graphs (fig. 3), which represent the mean ratings of appropriateness for each of the five levels of contrast-obtrusiveness, and for each of the three settings utilized. The data are shown separately for the factory and the lodge.

For both buildings there is an overall, monotonically decreasing function relating judged appropriateness to the contrast-obtrusiveness dimension. This function varies according to the particular context in which the building appears. Statistical analysis reveals the color-contrast variable to be significant beyond the 0.001 level for both buildings, and the interaction between color-contrast and level significant beyond the 0.001 level for the factory and beyond the 0.02 level for the lodge. The graphs indicate the source of the interaction in the case of the factory is in the plain-undeveloped setting, for which the differences among the various colors were least (i.e., the slope of the function was the most shallow). In the case of the lodge,

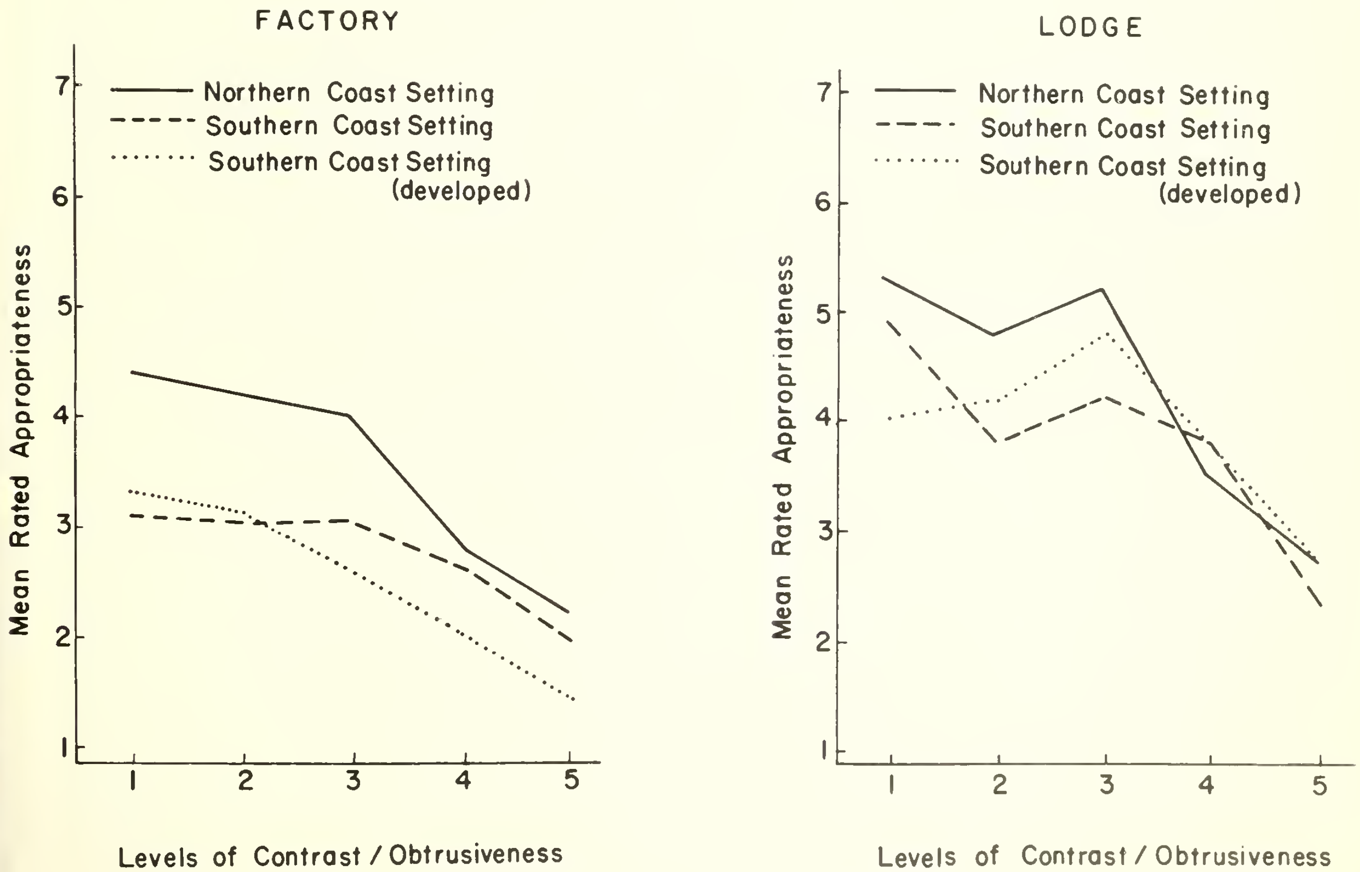

Figure 3.--Mean ratings for appropriateness for factory and lodge, as a function of setting. (Note: "Northern Coast" refers to "scenic" setting; "Southern Coast" refers to "plain" settings.)

it was the plain-developed setting which resulted in the most shallow slope, compared to the other two. It might be noted that overall differences among the three contexts were significant only for the factory ($p < 0.001$); the direction of the effect is apparent from the graph. Finally, overall the appropriateness ratings were consistently higher for the lodge than for the factory.

A final effect relates to the difference between the students in the two groups. The environmental-design majors generally rated the buildings as lower in appropriateness than did the unselected introductory-psychology students ($p < 0.05$). More significant, however, is the finding that, in the case of the lodge, the environmental-design students responded much more strongly to the contrast-obtrusiveness variable (i.e., the slope of their function was considerably steeper). The interaction between group and level was significant beyond the 0.001 level. While the results in the case of the factory were in the same direction, the interaction between groups and levels was not significant.

No relationships were found between the familiarity ratings and the appropriateness ratings, nor between the appropriateness ratings and the civilism-wildernism scores.

Subsidiary Results

The data graphed in figure 3 suggest little difference between the first three levels of the contrast-obtrusiveness scale. Introduction of the white-red versions, particularly in the case of the lodge, created the major effect of this variable on appropriateness ratings. The role of the two variables of color-contrast and size-obtrusiveness was investigated separately, using sets of slide-triads varying only in color (three levels) with size constant at the intermediary level, and only in size (three levels) with color constant at the intermediary level. These comparisons were limited to the scenic and the plain-undeveloped contexts (i.e., the plain-developed context was not utilized).

The results shown are presented in table 1. The statistical analysis indicates significant effects for both color and size ($p < 0.001$ in each case), but for both variables the effects are concentrated in the change between the second and the third levels, corresponding to the shift from the gray-brown to the white-red color, and from the intermediate to the large size (and, in the case of the factory, the auxiliary structures). For both variables the overall ratings were higher for the lodge than for the factory, as they were in the main study (fig. 3). In the case of the size series, the effects of levels of size-obtrusiveness differed for the two structures: the drop from level 2 to level 3 was much sharper in the case of the lodge (where it corresponded to a change from a two- to a four-story building) than the factory. The interaction between the two variables was highly significant. In the case of the color series, the role of the color-contrast variable differed for the two settings: in the scenic context, appropriateness changed little from level 1 to level 2, but dropped precipitously between levels 2 and 3, whereas in the plain context there was a fairly regular decrease from level 1 to level 3.

These findings thus show clearly the scale of contrast-obtrusiveness that we devised for this study is far from linear in its effects. The change from the intermediary to the high level of both the color and the size manipulations produced the major effects; it appears the two variables contributed approximately equally to the overall effects shown in the main study.

Table 1.--Mean appropriateness ratings for "factory" and for "lodge" as a function of differences in color only, and in size only, for "scenic" and "plain" settings

	Factory Levels			Lodge Levels		
Color series	1	2	3	1	2	3
"Scenic" setting	3.7	3.4	2.0	4.9	4.8	3.3
"Plain" setting	3.6	2.9	2.9	4.2	4.4	3.6
Size series						
"Scenic" setting	3.7	3.3	3.3	5.6	5.3	3.7
"Plain" setting	3.5	3.4	2.2	4.3	4.6	3.0

REPLICATION AND EXTENSION

The ratings asked of the subjects in the preceding study, to judge the "appropriateness" of the buildings to their settings, in effect suggested to them a semi-objective mental set, approximating that of the landscape architect or designer in drawing up plans for such a building, or that of an architectural critic providing a professional evaluation of the building. A different type of rating directed at a more subjective response to a building or scene in terms of the viewer's sheer affective reaction to it might well have yielded different results, notably in the sense of a possible inverted-U-shape function such as has frequently been observed heretofore in relation to the attribute of diversity or complexity of stimuli. That is, individuals may well prefer an intermediate degree of contrast between a building and its natural setting, even if they judge it as less than optimally "appropriate" in its context.

A further study was undertaken to compare judgments of appropriateness with ratings of liking on a "like very much" to a "dislike very much" scale. It was not possible to obtain these ratings with a group of California subjects equivalent to that used in the first study. The new subjects were Pennsylvania students. An opportunity thus arose to determine additionally the generalizability of the previous findings to a new group of individuals residing in a different area of the country, specifically outside of a coastal area.

Stimulus series

Each subject made ratings of two series of 15 slide triads; each series contained triads of the factory in one of the 3 settings, in its 5 levels, and the lodge in a different setting in its 5 levels; the remaining 5 triads were filler items. Six subgroups of subjects were utilized, according to the design shown in table 2.

Between the 2 series of slides (i.e., the ratings of appropriateness and liking), the subjects saw a series of 15 individual slides of paintings by landscapes artists. Each slide depicted a prominent man-made feature. A further similar set of 15 slides of paintings followed the second set of the experimental stimulus series. These two sets were rated as part of a separate study.

Subjects

The subjects in this study were 58 students enrolled in courses in man-environment relations at Pennsylvania State University, predominantly sophomores and juniors. They included 41 males and 17 females; their mean age was 21.2 years. Through their course work they had had some exposure to problems in the general area of environmental perception, but no specific involvement in the type of problem of environmental esthetics dealt with in this study.

Procedure

The procedure followed was virtually identical with that described above for the first study, except for the special instructions for the ratings of liking, which specified the subjects were to rate each building in terms of how well they liked it on a seven-point scale from "like very much" to "dislike very much."

The adaptation of the "urbanism-wildernism" scale was omitted from this study, and the familiarity ratings were changed to refer to

Table 2.--Design of replication study

	Group					
Sequence of judgments	I L - A	II L - A	III L - A	IV A - L	V A - L	VI A - L
Factory-appropriatness ratings	S	PD	PU	PU	S	PD
Factory-liking ratings	PU	S	PD	S	PD	PU
Lodge-appropriateness ratings	PD	PU	S	S	PD	PU
Lodge-liking ratings	S	PD	PU	PD	PU	S

Note: S = "Scenic" PU = "Plain-Undeveloped" PD = "Plain-Developed"

coastal areas generally, rather than the California Coast, in deference to the change in geographic locale.

RESULTS

The main results from the replication and extension are shown in figure 4. They confirm those obtained with the California sample only in part. That is, the appropriateness ratings varied significantly as a function of contrast-obtrusiveness for the Pennsylvania students, just as they had for the California students, but the relationship was less consistent and more complex. In the case of the factory, there was an overall decrease in appropriateness with contrast for all groups combined, but as figure 4 shows, this effect was virtually absent in the case of the "scenic" setting, which was precisely the one showing the steepest gradient in the previous study. In the case of the lodge, there is an unmistakable indication of an inverted-U-shape relationship, such that an intermediate degree of contrast is regarded as most appropriate. (In the California data there was, in fact, a similar pattern for judgments of the lodge, under the "plain" setting in the developed version in fig. 3).

As for the other major variables, it is clear for both ratings (appropriateness and liking) the lodge rates higher than the factory, as had been found previously. The role of context shows up significantly only for the lodge, where the scenic setting appears to enhance both appropriateness and liking ratings relative to the two plain settings. In the case of the factory, on the other hand, the interaction between setting and color-contrast found in the first study did not appear in the replication. Instead, for both ratings there was a significant interaction between the contrast variable and the sequence in which the two ratings were made. The interaction took the following form (for both appropriateness and liking): whichever rating occurred first showed a rather irregular, inconsistent change with contrast, while that occurring in the second half of the session showed a rather steeper, roughly linear function. (Thus, the functions for the factory shown in figure 4 are in fact composites of two rather different functions, depending on whether the judgments in question were made in the first or second half of the session.)

DISCUSSION

The results from both the original and the replication study are consistent in one significant respect: they provide concrete testimony to the efficacy of the contrast-obtrusiveness as a primary determinant of rated appropriateness of buildings to their natural surroundings. For both the factory and the lodge, and for both California and Pennsylvania students, the contrast-obtrusiveness variable was a highly significant source of variance of these ratings. The same point applies to the measures of preference (i.e., the ratings of "liking") obtained in the replication study.

This effect appeared to be concentrated at the two upper levels of the contrast-obtrusiveness variable, which (with the exception of the ratings of the lodge in the replication study) yielded consistently low values for both appropriateness and liking. The stimuli at these levels all shared a gleaming white color for the walls of the buildings and a saturated red roof. In addition to the role of the color, the differences encountered in the ratings for levels 4 and 5, involving a marked increase in obtrusiveness (through increase in size and, in the case of the factory, addition of auxiliary buildings) shows the importance of the obtrusiveness dimension, which was corroborated by the supplementary data from the first study relating to the effects of obtrusiveness with color kept constant.

The pattern at the lower levels of the contrast-obtrusiveness variable is less clear. In the first study judged appropriateness showed a generally monotonically decreasing trend as contract increased. The second study revealed suggestions of an inverted-U-shape function, pointing to a possible optimal level of contrast. The fact this optimization trend applied to both the "objective" (i.e., appropriateness) and "subjective" (i.e., liking) data suggests the subjects did not differentiate clearly between these two judgments. At the same time, this finding argues against the view that individuals may personally desire some modal degree of contrast in the environment, while under a more objective mental set they consider a minimum of such contrast as most appropriate--a hypothesis that on the basis of the results of the first study appeared tempting.

Clearly, other variables apart from amount of contrast were important to the subjects as well. The context variable yielded frankly inconsistent results over the two studies, but the tendency of ratings to be most favorable under the scenic setting suggests the operation of a halo effect: instead of judging a building as particularly inappropriate or disliking it most strongly because of its appearance in a highly scenic setting, the subjects tended to give that building the most positive ratings in the scenic setting, possibly because the attractiveness of the setting spilled over, into the judgments of the building itself. (The higher values obtained in the first study for the scenic setting in the case of the factory suggested an alternative interpretation: the wooded surroundings provided a more relevant context for a lumber mill than the other, treeless setting. Yet, in the second study the lodge was rated most favorably in the scenic setting; thus the halo explanation appears to be a more tenable one. Admittedly it fails to account for the lack of a similar effect for the factory in the second study.)

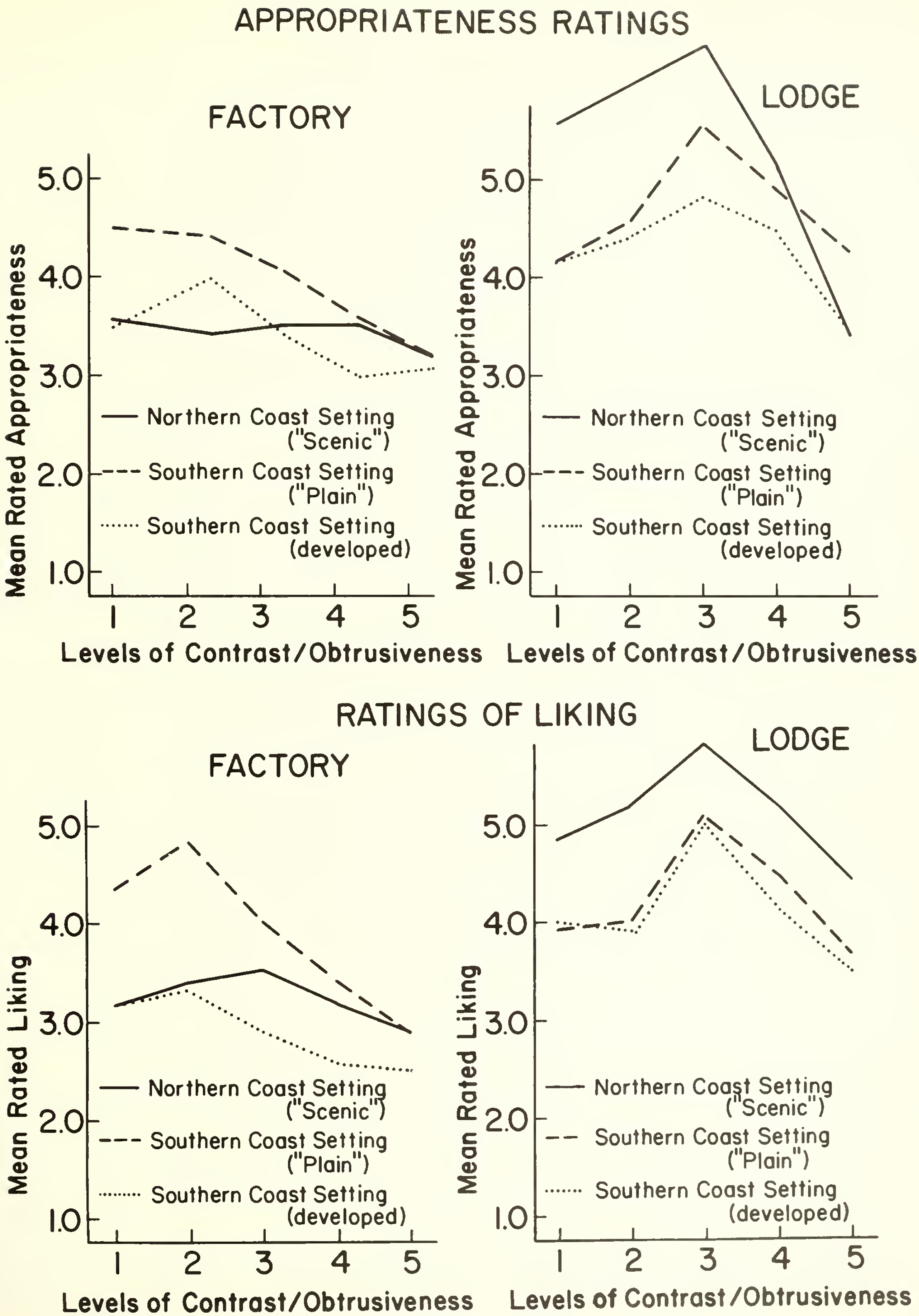

Figure 4.--Mean ratings for appropriateness and liking for factory and lodge, as a function of setting. (Replication Study.)

The data in both studies show more positive responses to the lodge than to the factory. This result in itself is hardly surprising or even noteworthy--one would hardly have predicted otherwise, whether on purely esthetic grounds, or on the grounds of the functional suitability of the two types of structures in these natural settings, or the associations evoked by each.

More interesting is the finding in the replication study that this difference was most pronounced under the scenic setting, as had in fact been hypothesized. The results obtained in the California study did not show such an interaction; indeed, the results came out in the opposite direction. Rather than attempting any purely post-hoc explanations for this discrepancy, it seems best to leave it as an unanswered puzzle, hopefully to be clarified through further research.

The differences between the results obtained from the two populations, both in regard to the difference in the effect of the setting on the ratings of the factory, and in regard to the different shape of the function relating appropriateness to contrast for the lodge, obviously raise the question of what role person-based variables play in esthetic or evaluative judgments of this kind. The California study did disclose a significant difference between the environmental-design students and the unselected students: the former showed greater sensitivity to the contrast variable, as expected. Neither general orientation towards civilization versus wilderness nor sheer familiarity with the coastal settings showed any significant correlations with the judgments, however. A more intensive effort to assess the individual's frame of reference in making the judgments in question is clearly called for. The subjects' associations towards the types of buildings being evaluated, and the subjects' views of the function of those buildings in their particular settings remain unknown. What is suggested here is a comparison between individuals who can be presumed to differ in their attitudes (e.g., between coastal residents for whom the "lodge" might have a direct economic benefit, and conservationists who might not see the lodge as potentially beneficial to themselves).

Finally, the comparison made between "appropriateness" and "liking," although not intended for the purpose, appears relevant to the differentiation that Craik and Zube have offered between preferential and comparative judgments, the former being considered more subjective (e.g., judgments of liking), and the latter involving explicitly or implicitly, reference to some objective standard (e.g., comparison of two buildings in terms of successfulness of the design). It would seem the appropriateness judgments used in this research come close to this comparative model of judgment, at least in the sense of implying a quasi-objective standard against which a given scene is judged. Thus, the fact the two sets of judgments differed little from one another in the replication study, and more particularly that the inter-individual variability of the two sets was closely comparable (whereas Craik and Zube had suggested that consensus should be greater for the comparative than for the preferential judgments) suggests the distinction is in need of further refinement. This conclusion is in line with the findings of Zube et al. (1975), which pointed to rather high intercorrelations between preferential responses and evaluative ones (considered to represent the comparative type), specifically ratings of liking and judgments of scenic quality. Substantially lower correlations, on the other hand, were obtained between either of these measures and more functionally based preference ratings (i.e., preference for each scene as a setting for a particular type of activity).

CONCLUSION

The findings from the present study, along with similar research by the author, as yet unpublished, carried out with ready-made stimuli taken from real environmental scenes scaled for contrast and obtrusiveness, bear out clearly the importance of the contrast-obtrusiveness variable as a determinant of people's affective and evaluative responses to the outdoor environment and confirm that the manner in which man-made structures are integrated into a natural setting is important to the esthetic satisfaction people derive from that setting. The findings should thus be of relevance to the managers of our natural recreation areas and scenic areas more generally, and more particularly to those involved in the design of man-made structures and facilities in these areas.

The findings do not offer a clear prescription for the ideal form such designs should take, not only because the data were not fully consistent, but more importantly because of the limited nature of the population sampled in this research (i.e., groups of college students). Further extension of this research to other populations would clearly be desirable. Nevertheless, solutions such as those envisaged in the recommendations of the California Coastal Zone Commission (1975) for the regulation of development in coastal areas, emphasizing a deliberate blending of all designs into the landscape, in terms of color, texture, and form, and a minimizing of any sense of standing out of the structure from its setting, must be regarded with some suspicion. Undoubtedly both the nature and function of the structure, and the characteristics of the setting will prove to be important aspects of the situation that must be taken into account in formulating guidelines for the design of such development. While the findings suggest a high degree of contrast and obtrusiveness is considered as incongruous, and thus negatively evaluated, some intermediate degree of contrast will, in many instances--such as a residential development in a scenic area--prove optimal. One need only consider the charm of a typical fishing

village with its prevalence of white buildings set off against the oceanfront, or a colorful lighthouse along a seaside bluff, to recognize the falsity of an over-simplistic constrast-minimizing approach to relating the man-made to the natural realm.

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A METHODOLOGY FOR SIMULTANEOUSLY

OBTAINING AND SHARING INFORMATION[1]

Rachel Kaplan[2]

People's perceptions of and preferences for particular environments have increasingly become the object of study. One may wish to know what environments people consider scenic, how they view particular practices such as strip mining or clearcutting, what feelings they have about the countryside. One wants to know what people notice, what they care about, and how they might view changes. Do they experience the environment differently depending on their background or situation, on their familiarity with the setting, or are these largely idiosyncratic reactions?

Two kinds of issues must be faced when people's perceptions and preferences are studied. One of these involves how the environment under consideration is presented or represented. The other issue deals with the dependent variable--the basis for the inference one makes about people's reactions. Both issues present numerous problems which have a direct impact on the utility of the results. While there is surely no one right way to approach either of these issues, there seem to be a variety of ways that create unnecessary problems.

The purpose of this paper is to illustrate through several diverse studies the advantages of a particular approach to these two issues. The approach is simple and straight forward; the results have been both useful and enlightening. Some of the requirements of the method will be discussed after a brief description of the approach and the sample studies.

PHOTOQUESTIONNAIRE

The common procedure utilized in the studies discussed here is a photoquestionnaire. The pictures, all black-and-white and only about 5 x 8 cm in size, are printed (offset) with eight photos to the page. The studies have varied in number of pages of pictures ranging between three and six. Participants are encouraged to look over all the photographs before responding. As such, the collection of pictures conveys information about the kind of environment under study. The studies all included verbal items in addition to the photographs, but these are not pertinent to the discussion here.

Participants are asked to rate each of the photos on a five-point scale to reflect their preference for the scene. The instructions all say something like "please indicate for each picture how much you like it." Each of the photographs has the numbers 1 to 5 immediately below it, and the participant circles the appropriate value according to instructions. The task is simple and presents no difficulties. (Two of the studies also included familiarity ratings for each of the photos.)

The studies reviewed here share one other feature: The participants in each case had at least some familiarity with the kinds of scenes pictured. That is not to say that all scenes were known to the participants; in fact, in several cases unfamiliar scenes were intentionally included. In each study the photographs were predominantly of the immediate environment of the participants at the time they were responding to the photoquestionnaire.

SOME SAMPLE STUDIES

The first study discussed here was carried out for an agency and as such can be considered "applied." But that study, as well as the three doctoral dissertations which constitute the other examples, cannot be classified in terms of application. All of them were carried out in the field as opposed to the laboratory, with "real people" as opposed to subjects, and had professional groups interested in utilizing the results.

At the same time, all four studies were designed to increase available knowledge about environmental esthetics. While practical results were important, insights into the theoretical underpinnings of this area were no less salient. The informational framework discussed at various times in the context of landscape preference (R. Kaplan 1977b, S. Kaplan 1975) provided the orientation for each of the studies. While the description of the studies here does not include

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1/ Paper presented at the symposium on environmental esthetics at the Ninth Annual Meeting of the Environmental Design Research Association, University of Arizona, Tucson. April 10, 1978.

2/ Author, Associate Professor, School of Natural Resources, University of Michigan, Ann Arbor.

the results, each has found the informational properties to be powerful predictors of landscape preference.

Study 1: Storm drain in a residential area

In Michigan each county has an elected drain commissioner. In the local county some citizens lodged complaints about the open storm drain overflowing into their gardens. The drain in question is about 5 miles long and passes through residential areas representing a wide spectrum of economic conditions. Not surprisingly, the same waterway is an attractive creek in some areas and a shoddily fenced-off eyesore in some other areas. The drain commissioner hired a landscape architect/planner to propose modifications and improvements to the drain, and research was designed to determine the residents' perception of this local feature of their environment.

It was decided words would be insufficient for such a task. As is true of so many environments, one experiences them in a nonverbal way. Strong feelings can be expressed without much difficulty; distinct activities carried out in such a setting can be described; but beyond that, "perceptions of a drain" would not make for easy conversation! Pictures seemed a necessary feature of the study. They could also serve to elicit reactions to potential changes in the drain, thus permitting insight into how modifications would be viewed in addition to perceptions of existing conditions.

The few pretests conducted were most instructive. Several residents who live right along this open storm drain had no idea what interviewers were inquiring about when told the study was about the Swift Run Drain, or the creek that is near their home. As soon as they glanced over the pages of photographs, however, they understood what it was about. The creek, or drain, or whatever it was for them, was a nameless part of their immediate environment; yet they knew it well.

The photographic portion of the questionnaire consisted of 4 pages with a total of 32 scenes (see fig. 1). These included views of the drain all along its course, photos of drains in other parts of the city, and a few scenes from other states. Participants, in all cases residents whose dwellings bordered on the drain, were asked to indicate both how similar their view of the waterway near their home is to what is in the picture and how much they would like that waterway to look like that picture. The photo-questionnaire thus served the dual function of providing information about the environment and eliciting responses from the participants.

The preference ratings are a source of much more information than likes and dislikes, per se. Examining the most and least liked pictures can certainly be instructive. Beyond that, however, the preference ratings can also show what are perceived as similar types of environments. Then, by examining the preferences for these dimensions or themes, one is in a much better position to anticipate problems in proposing changes, or for that matter, in deciding to leave certain areas unchanged. In the case of the Swift Run Drain, water was not always perceived as an amenity; there are waterscapes that are distinctly unpreferred.

The questionnaire also included verbal analogues to some of the pictured dimensions. The differences in reactions to the visual and verbal formats are informative. I think it is fair to say the verbal descriptions were more likely to lead to stereotypic responses. Thus for residents in the area where the drain had most problems, the thought of piping it underground provided one easy way to eliminate the mess. Photographs representing various versions of a covered drain, however, were not viewed as favorably. On the other hand, appreciation of particular pond-like arrangements need not conjure up the health hazards a few people mentioned in reaction to the verbal description of a body of water left natural, marshy. These findings suggest one can easily be misled by relying on either visual or verbal material alone. Each approach provides some insight into the domain being sampled. A more extensive discussion of the study can be found in R. Kaplan (1977a).

Study 2: Natural landscape in the urban context

The CUNA Mutual Insurance Society office in suburban Madison, Wisc., was the site of Tomas Gallagher's (1977) doctoral dissertation study. The 15 acres of land around the four-story CUNA building are in part maintained as an ornamental landscape with mowed expanses and diverse trees, but major portions of it have been converted to a prairie and woodland restoration, or natural landscape. Gallagher was interested in studying people's preferences for these two distinctly different kinds of landscapes. He desires to introduce more natural landscapes within urban areas, and yet as a landscape designer he was aware such arrangements are not always met enthusiastically. His study involved a test of the informational framework in predicting landscape preferences; his goal was to identify approaches one might use to "achieve public acceptance of natural landscape proposals" (p. 20).

The CUNA landscape experiment is widely known, and CUNA permits use of the grounds for educational field trips. The natural landscape is visible from the CUNA building and the surrounding residential area. The CUNA management was most cooperative with Gallagher's study and permitted a random sample of their 800 employees to participate. In addition to the 137 CUNA employees, the study included a sample of homeowners and apartment dwellers who live immediately adjacent to the CUNA grounds.

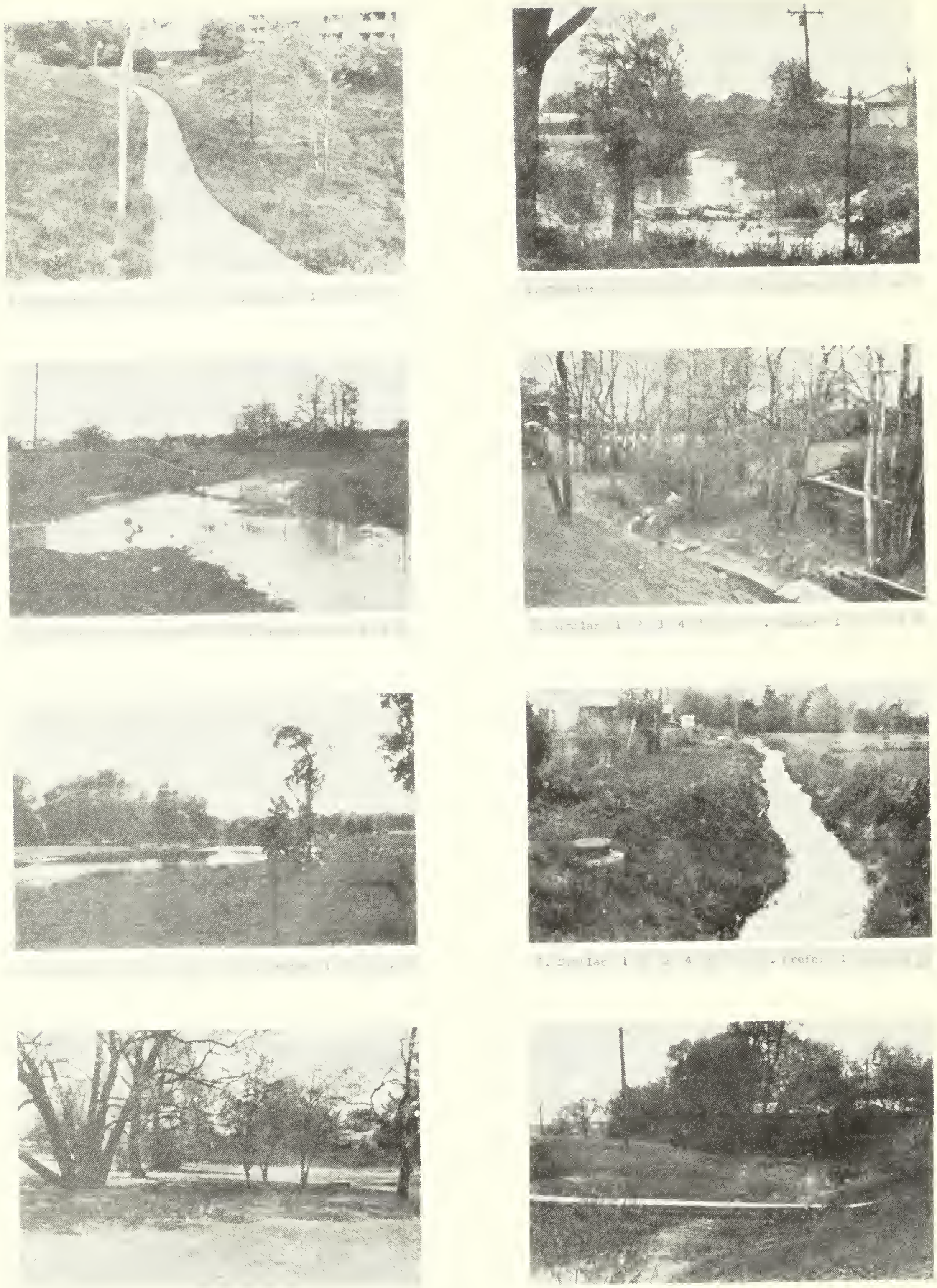

Figure 1.--A sample page from the drain study photoquestionnaire.

All participants indicated their preference for each of the 32 photographs that were taken on the CUNA grounds. The four pages of photos represented the range of settings available in the landscape program there (fig. 2). Pictures were taken at eye level; some included the CUNA building in the picture. In addition to the participants' preference ratings, a panel of judges rated each photograph in terms of a number of predictor variables representing the informational framework underlying the study.

Study 3: Forest practices in a rural setting

Eddie Anderson's dissertation (1978) is also concerned with residents' perceptions of their nearby environment. The setting in this case, however, is a western Michigan rural county where commercial forestry is the principal industry. Most of Lake County is within the boundaries of either national or state forest land. The county's population is low (under 6,000), and unemployment is high (about 13%).

The scenes in Anderson's photoquestionnaire are of hardwood forests, pine plantations, and logged areas. They represent an unspectacular natural environment that is characteristic of the region (fig. 3). All but 2 of the 48 scenes depict local natural settings; they were selected to sample the variety of management practices in use in the region. Although lakes and streams abound in the county, waterscapes were excluded from the study.

One of Anderson's objectives was to compare the environmental preferences of various local groups: blacks and whites, high schoool students and older residents, those with longer term acquaintance with the area, and relative newcomers. The differences between management professionals and the local people are also of interest. In all, some 300 people responded to the survey. They were told the study dealt with the natural surroundings in their area and how "people relate their daily activities with the natural surroundings during both work and leisure time. We would like your help in finding out more about the role that the natural environment plays in the lives of local people."

Anderson found people were, by and large, happy to participate in the study. Many expressed delight with the picture-survey. Even though the photoquestionnaire was quite long (6 pages), people needed little encouragement to complete it and to continue with the remaining pages of questions.

Study 4: Visitors at a bog environment

The setting for William Hammitt's (1978) dissertation study is the Cranberry Glades Botanical Area in the Monongahela National Forest in West Virginia. Unlike those in the other studies, the participants in this case were not in their home or work environment, but rather visitors to the bog. About 60 percent of them were residents of the same state, but for none of them are the Glades in their everyday environment. Hammitt asked some 400 visitors to complete his photoquestionnaire right at the end of their short hike on the bog trail. All were asked to indicate their preference for each scene, and some were also asked to rate the scenes in terms of how familiar they appear.

Included among the 24 photographs were scenes of the various habitats along the trail, scene of the boardwalk itself, and also some scenes the visitors could not have seen on that hike (fig. 4). Some of these were from the same area (e.g., an overview) and others were from a bog environment in another state.

Hammitt was interested in studying the role of familiarity in preference. He examined the preferences of first-time visitors versus repeat visitors, as well as the preferences of people who were shown photographs prior to their hike versus those who saw them only at the end. These comparisons led to some important insights about the role of a leisurely, recreational outing in people's experience of the environment. The photo dimensions, or themes, based on the preference ratings, also shed light on ways to manage and interpret such settings.

SOME COMMENTS ON THE APPROACH

The photoquestionnaire approach has shown itself to have many advantages. First, the method is meaningful to the participants. Not only do they have no difficulty with the task, they enjoy it and invariably express appreciation at being asked to participate. The photos need not be of a high quality, nor are color images necessary. By having the scenes printed, as opposed to projected, the task becomes self-paced and participants can go back and forth over the pages. The participants in the studies described represent a wide range of backgrounds, ages, and abilities. Looking at pictures is not too demeaning for a professional, nor too demanding for a child.

The procedure is inexpensive, manageable, and interesting for the participants, hardly trivial considerations if one takes citizen participation seriously. It is easy to ignore citizen input when the participants seem inarticulate, confused, or even hostile. Given the chance to participate in a meaningful way, citizens give insights and opinions that can be important components in decisionmaking.

Presentation of the environment

In any environmental assessment the issue of presenting or representing the environment must be considered. An important distinction here involves whether or not one is dealing with an existing environment or situation or one that is being proposed.

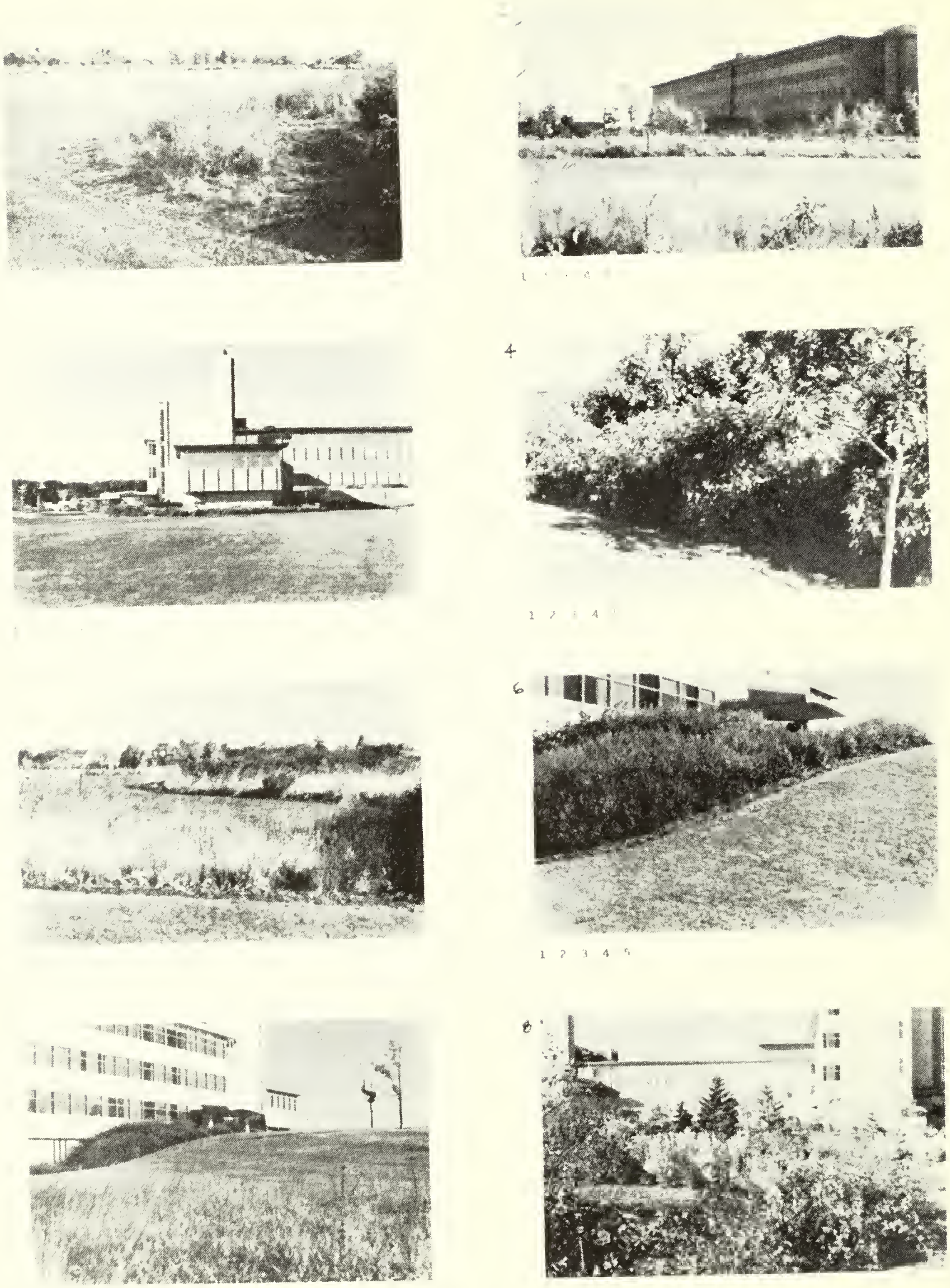

Figure 2.--One of the pages from Gallagher's photoquestionnaire.

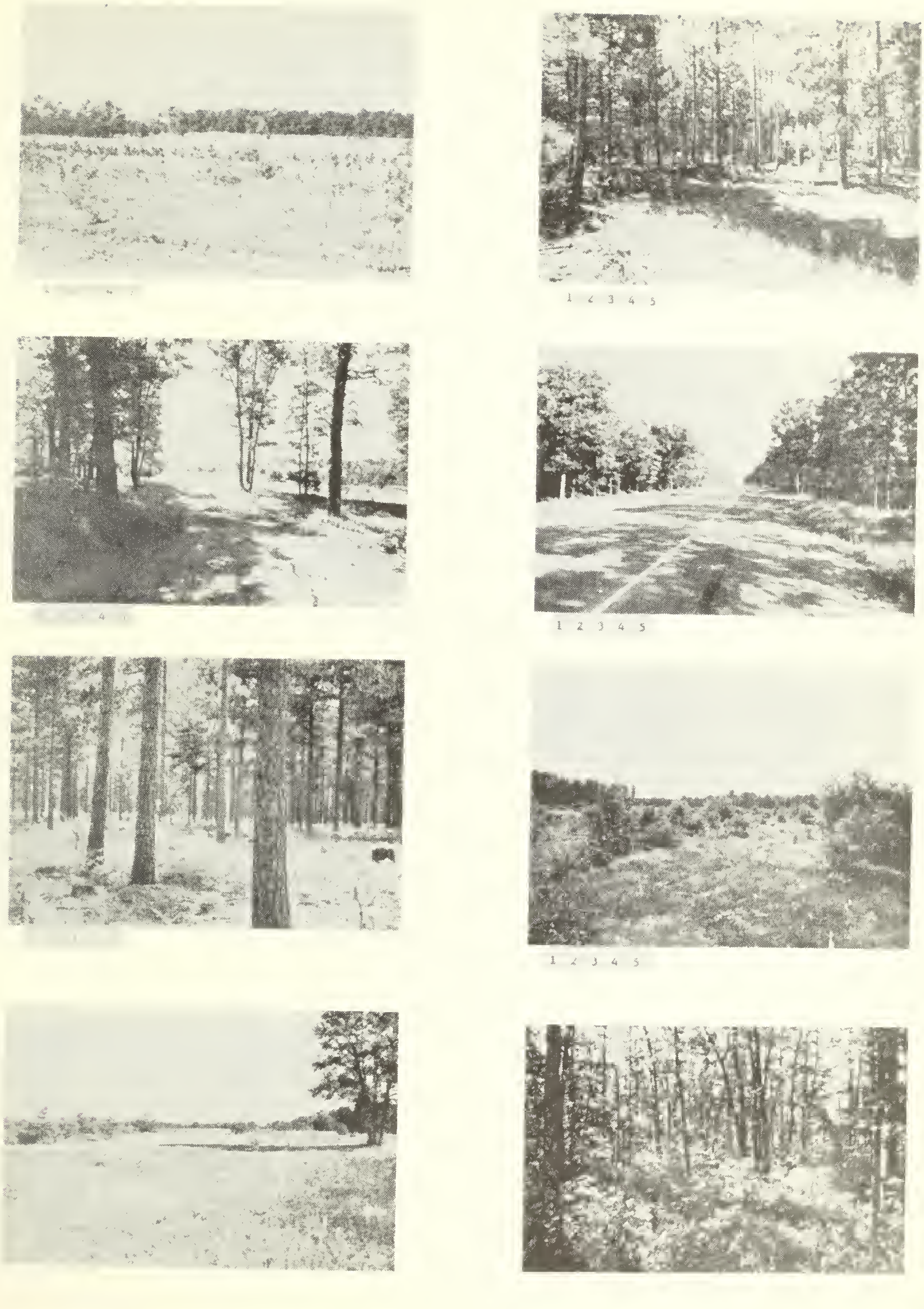

Figure 3.--An example of the photoquestionnaire in Anderson's study.

Figure 4.--Sample page from Hammit's bog study.

There is no single foolproof or accurate procedure for presenting an environment. One can lie with statistics, with words, and with pictures. But photographs do have several advantages. They lend themselves to presenting existing conditions in the study area and comparable areas elsewhere. One can also photograph simulations of an environment, creating visual images of possible alternative solutions. Furthermore, including a variety of pictures of the setting in question does not add much time or expense to the cost of conducting a study. The participants' impressions can be based on a range of examples rather than on one or two instances.

The four studies all used photographs of existing environments. A modification of the procedure described here was used in a study of a proposed downtown park, using photographs of models. In this case, 24 views of possible scenes and settings within the park were presented using 7.5 x 11.5 cm photographs mounted on 4 boards (28 x 33 cm). The scenes were generated from three alternative designs for the park, but participants were asked to react to the individual scenes rather than to the design alternatives. Participants could view the photographs and register their preferences at either the public library or bank lobby, both in the immediate area of the proposed park. For a fuller discussion of this study, see R. Kaplan (1978).

The presentation of the environment is of central importance. Although it is rarely acknowledged as such, the quality of the responses one obtains from participants is necessarily a function of their comprehension of the environment under study. If people are not certain what setting or changes are being discussed, they are put in a difficult situation. The maps and graphics that are so frequently part of public meetings are baffling to many people in the audience.

The selection of photographs must not be taken lightly. The photographs provide information about the setting or changes that are the subject of the study while at the same time being the object of participant reactions. The range of pictures selected must be extensive enough to reflect the full range of conditions present in the study area. In fact, not only is it possible to show and obtain information at the same time, effective sharing is essential if information obtained is to have any validity or usefulness.

Selection of photographs must thus entail two considerations: adequate sampling and the possibility of comprehension. The photoquestionnaire format can easily accommodate some 20 to 40 pictures. This permits judgments of possible alternatives and of a range of examples of each of the settings within the study. Rather than relying on a single instance of a dense woods or open bogmat, for example, there can be three or four instances of such settings. As with any measurement situation, one is on safer grounds having several items represent people's reactions rather than relying on a single instance.

Comprehension is facilitated by having visual material, but all graphic material is not equally effective in communicating information. The problem of comprehension is particularly acute when communicating about environments not yet existent. But even for existing conditions, one can select photos that are difficult to understand, that provide too much detail, or that fail to communicate scale. It is hard for the professional to realize, but some graphic material is more confusing than helpful (S. Kaplan 1977). Pretesting the material with a group of nonprofessionals is essential.

Extensive sampling of the environment has one further advantage that should perhaps be mentioned. While the studies have direct application to field settings, they need not compromise the desire for more systematic and controlled approaches possible in the laboratory setting. In photographic form, the scenes are highly transportable and can be taken to the participant. But at the same time, by careful selection of the visual material, many hypotheses can be tested, and the basic knowledge of environmental preference can be advanced.

Getting the information

There are many ways to study people's reactions. Public participation often involves public meetings where those who wish speak their minds. One is often tempted to ask people what they like and why they prefer certain settings over others. These questions turn out to be much easier to ask than to answer. Given the frustration such a seemingly direct approach yields, some researchers opt to stay clear of asking anything. Instead, they record how places are used. These observations then are used as an indication of environmental preferences. While it might be safe to assume that a well worn path across the lawn suggests a place where some would like a walkway, some other inferences based on observations are more controversial. One highly regarded social scientist has been telling us that crowded sidewalks in New York City are an indication of preference. He even shows some pictures of people smiling. (He does not mention the crowded subways, however.)

One approach to getting people's reactions is based on the preference ratings, using a five-point scale. People seem to have no trouble with this task. Indicating how much they like a scene is manageable and enjoyable. Because there are a number of scenes to rate, each one need not be belabored. Because they are not rating each scene for a multitude of adjectives, many more scenes can be included in the study.

As indicated earlier, the simplicity of the procedures does not limit the richness of resulting insights. Knowledge of the preferences of

particular scenes is valuable to a certain degree. If one only shows people a handful of pictures, then the preference for each is all one has to examine. With 20 to 40 scenes, however, the preferences for each item becomes less instructive. One quickly discovers scenes representing comparable environments from the professional's point of view, may be regarded as quite different in terms of the citizens' preferences.

By subjecting the preference ratings to dimensional analyses, one can determine much more than which scene is liked and which is not (R. Kaplan 1974, 1975). Validity and reliability are both enhanced by the use of many instances. The dimensional procedures provide an indication of the internal consistency of each factor or grouping. The Cronbach Coefficient Alpha value across these studies ranges from the 0.70's to the 0.90's. In fact, one can begin to get answers to the elusive question of why some settings are preferred. The patterns of preference ratings, as opposed to the particular examples, provide an indication of the underlying similarities among the scenes in the study from the perspective of the participant. To some extent these themes or groups parallel the basic categories used in a typical visual resource assessment. To the extent that they do not, they are particularly useful in extending our insight in the area of environmental perception and preference. For a discussion of the sorts of groupings of content obtained in these and related studies, see S. Kaplan (1978).

Using photographs hardly constitutes a new method, but the procedure described here has many attractive features even if novelty is not one of them. The interrelated problems of providing information about an environment and asking information about it are easily accomplished by using a variety of examples through photographs. The method is inexpensive and readily adapted to many problems of environmental assessment. The photoquestionnaire combines elements of laboratory slide rating experiments, surveys, and interactive participatory procedures. It is a method that is meaningful to participants and allows them to proceed at their own pace. The method lends itself to providing alternatives that can be compared in parallel and permits extensive stimulus sampling.

The procedure has been received enthusiastically not only by the participants; agencies involved in the studies have also enjoyed the process and received the results eagerly. After all, generating information that is both useable and useful is an urgent need in the area of environmental preference.

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MEASUREMENT OF PREFERENCES FOR

PROPOSED LANDSCAPE MODIFICATIONS[1]

John H. Schomaker[2]

Public involvement and input are common and accepted parts of public land management today. Public meetings and workshops are an integral part of the USDA Forest Service land use planning process, for instance. The public is frequently given the opportunity to evaluate proposed classification or management alternatives. The public has not been routinely included, however, in decisions primarily concerning esthetics. The shape of a clear-cut, the route of a transmission line, or the layout of a road have generally not been included in the public involvement framework.

Evaluation of proposed landscape modifications has primarily been the concern of professional landscape architects. Professionals have assumed that their standards of scenic beauty are the same as the public's. Professionals design and implement landscape modifications, but the untrained public ultimately evaluates the scenic quality resulting from these management decisions. Recent legislative efforts and legal suits indicate professionals can no longer base decisions solely on what they deem best, ignoring public input. Public input to the decision-making process reduces the discrepancy between public land management goals and public desires.

Given present circumstances, the primary objective of this study was to develop a methodology to determine public preference for alternative forms of proposed landscape modifications. Ideally, in this kind of method development it would be desirable to measure people's preferences for sketches of proposed landscape modifications, make the modifications, and then measure people's preferences for the actual field modifications. The costs and technical requirements of this ideal situation are prohibitive. The study was simplified in an attempt to determine whether preferences for sketches can be used to predict preferences for photographed scenes.

Given the wide range of scenes and modifications of interest in this study, photographic slides were chosen as the primary or reference stimuli. Transporting observers into the field would have been too costly, and past workers (Boster and Daniel 1972; Shafer and Richards 1974) have found agreement between field observations and ratings of slides.

A second objective of the study was to determine the extent to which public and professionals agreed on preferences for proposed landscape modifications. The procedure and results of this substudy are discussed below with the main study.

PROCEDURE

Color slide representations of 48 landscape scenes depicting timber harvest areas, roads, utility installations, and ski slopes in otherwise undeveloped mountain areas were selected for the study. The modifications exhibited various degrees of "naturalness" and varied in distance from the camera. The slides included 19 timber harvest areas, 14 roads, 12 utility installations, and 3 ski areas.

All the landscape scenes were also represented as black-and-white and color sketches. An advanced student in landscape architecture first prepared a black-and-white sketch from each landscape slide. A copy of each black-and-white sketch was then tinted to approximate the coloration of the original slide. Both the black-and-white sketch and the tinted sketch were then photographed to produce slides for presentation to observers.

Black-and-white sketches were also selected from the USDA Forest Service publications, "Forest Land Management" and "National Forest Landscape Management," to illustrate 32 different landscape modifications designed by professional landscape architects. The sketches selected included nine pairs depicting several timber harvest options, utility installations, and roads. All of these sketches were photographed and represented in the study as slides. In addition, two series of seven slides each were also selected.

1/ Paper presented at the symposium on environmental esthetics at the ninth annual meeting of the Environmental Design Research Association, University of Arizona, Tucson April 10, 1978.

2/ Author was Assistant Professor, Wildland Recreation Management, College of Forestry, Wildlife and Range Sciences, University of Idaho. Now with USDA Forest Service, North Central Experiment Station, St. Paul, Minn.

Each series depicted a variety of ways a particular area could be harvested: large and small scale harvests, and naturalistic, rehabilitative, and landscape deterioration methods. Because the preferences of professionals for each pair or series of scenes was given, these slides served as the basis for the professional and public preference comparison.

Based on the 48 original landscape scenes there were 48 color slides of the actual scenes, 48 slides of black-and-white sketches, and 48 slides of tinted sketches. This set of 144 slides was reduced by randomly eliminating 33 of the black-and-white sketch slides, leaving a total of 111 slides. In addition to this set, 16 duplicate slides were prepared to provide a test of observer judgment reliability; 1 black-and-white sketch slide, 11 tinted sketch slides, and 4 color slides of the actual landscape scenes. Combined with the 32 slides of professional sketches selected from Forest Service publications, a total of 159 slides were presented to the observer panel.

A total of 110 observers, students at the University of Idaho, rated the slides. The raters included 69 forestry students, 14 landscape architechture students, and 27 students from other disciplines.

The rating procedure was adopted from Daniel and Boster (1976). The observers were asked in standard instructions to evaluate each slide and assign a numerical value to the scene depicted. Values ranged from zero, indicating very low scenic beauty, to nine, indicating very high scenic beauty.

Observers were permitted 8 seconds in which to view and judge each slide, and record their ratings on computer optical scanning sheets. Slides of the black-and-white sketches, tinted sketches, and of the actual landscape scenes were shown in separate sets. The slides in each set were randomly ordered. Four sample slides were shown at the beginning of each set. An 8-second rest was included after every tenth slide and students were given a 5-minute break between sets. Computer cards were punched directly from the optical scanning sheets.

RESULTS

Throughout the data analysis the ratings were assumed to form an interval scale. Although this assumption is probably not totally valid, serious errors are not introduced by the assumption. Initially the rating data were transformed into $\underline{Z}$ scores to form an interval scale by means of the Law of Categorical Judgment (Torgerson, 1958). Compared to the analysis of the simple ratings, the $\underline{Z}$ transformation had only a small effect on relative scale values and resulting correlations. Because the complexity of the transformation calculations was judged counter to the intent of keeping the method simple to encourage its use to gain public input, it was decided to base all analyses on the simple observer ratings.

Judgment Reliability

Reliability of the ratings was estimated using a test-retest procedure based upon the 16 duplicate pairs of slides imbedded within the 159 total slides. A potential problem with comparing duplicates is the possibility that subjects would remember their ratings within a duplicate pair and consequently not give independent ratings. Rapid projection of the stimuli, mirror-image positioning of duplicates, random ordering, and the large total number of slides would all be expected to minimize the recall bias. The test-retest reliability was obtained by correlating observer judgments of the duplicate slide pairs. The average correlation for all 16 pairs was 0.67. Given that this reliability applies to the average test-retest reliability of a single scene, the magnitude is encouraging and acceptable.

Comparison of Alternative Representations

To determine the suitability of tinted sketches for representing landscapes and landscape modifications, ratings of the 48 slides of actual landscapes were compared to the ratings of slides depicting colored sketches of these same 48 landscape scenes. Average ratings for the color-sketch slides and the original landscape slides were used as the independent and dependent variables, respectively, in linear regression. The regression equation was $Y = 0.95 + 0.95X$, where X is the average rating of a color-sketch slide and Y is the predicted rating of the corresponding slide of the actual landscape.

Several aspects of the regression equation and related statistics are interesting and useful. First, the intercept (0.95) indicates that slides of the color sketches were generally rated one scale unit lower than the original landscape slides. Second, the slope (0.95) approximates unity, indicating that a one-unit increase in scenic beauty ratings for slides of the color sketches approximates a one-unit increase in the rating of the original color slides from which the sketches were made. The square of the correlation coefficient (0.74) indicates that 55 percent of the variance in Y is accounted for by X.

An estimate was made of the required difference between two predicted values before one could have confidence any two slides of different scenes were indeed rated differently. With 100 raters and a significance level of 0.05, the difference in mean ratings required for two scenes to be considered statistically different is 2.2. Thus, if two predicted scores are a little more than two scale points apart, one can be confident that one photograph is rated higher in scenic beauty than the other.

The sketches by the landscape architecture student had originally been accepted without

critical analysis. Subsequently, however, a three-member panel consisting of the two study investigators and a recreation planner looked at each slide pair projected side-by-side and independently decided whether the sketch depicted the actual landscape photograph well or not. After looking at all pairs, ratings were discussed and a consensus was reached for each pair. In general, there was little disagreement on the ratings. The sketches that were considered poor representations did not depict the color, depth, or distance of the actual photograph accurately. A typical problem was that modifications were much more pronounced in the sketches than in the photographs.

Ratings of color-sketch slides and of the original color slides were then related through linear regression for the scenes judged as being adequately represented by the sketches. The resulting regression equation was $Y = 0.59 + 0.93X$, with an R^2 of 0.71. Thus acceptance of sketches that were judged to be representative of the original color slides they depicted led to an increased predictive capability. The equation for the selected scenes might be thought of as a limit of predictability for this technique. The three panel members were able to compare the sketch directly with the actual photograph, an advantage not available for proposed landscape modifications. For those selected slides and 100 raters, 1.5 is the minimum difference between predicted means necessary for one to have confidence that the ratings were statistically different at the 0.05 level.

As a matter of interest, regression analysis was also performed on the slides of the 15 black-and-white sketches and the corresponding original color slides. The equation was $Y = -0.43 + 1.26X$ with an R^2 of 0.46. For this particular set of scenes, the tinting of the sketches resulted in a much better correspondence with ratings of the actual landscape slides; the R^2 for tinted sketches and actual photographs for these same scenes was 0.76.

An additional analysis was performed to gain insight into the ratings of color-sketch slides and landscape slides. The photograph-sketch correlations for the top and bottom quartile of scenic beauty ratings were compared. It was hypothesized that rater reaction to dominant man-made features in the landscape, such as geometric clearcuts and power lines, might be more consistent than those for landscapes with less dominant features. Correlation was calculated for pairs in which the color sketch had a mean rating of less than 2.66. A similar correlation was calculated for slide pairs with sketch-slide ratings above 4.21. The correlation coefficient for the bottom quartile of 12 pairs was 0.64. For the top quartile the coefficient was 0.10. Due to range restriction, the correlation coefficients are lower than the coefficient for all 48 pairs, but the difference between the correlation coefficients for the 2 quartiles is notable. Raters do respond more consistently to sketch slides and actual slides on the lower end of the rating scale. This is undoubtedly due to the dominant feature aspect of the landscapes on the low end of the scale and the poor representation of the more spectacular scenery in the sketches of the highly rated landscape scenes.

Comparison to Professional Judgment

The USDA Forest Service offers guidelines for landscape modifications in its series of publications, "National Forest Landscape Measurement." Nine pairs of sketches and two series of seven sketches each were selected from these publications and photographed for presentation to our observers. In no case did the "nonprofessional" raters' judgments of these scenes disagree with the professional preference for one modification alternative over another.

Ratings of both the seven-slide series of sketches were compared using Duncan's multi-range test. As an example, the results of Duncan's test for one of the series are summarized in table 1. The order of rating is consistent with the judgment of the professional landscape architect.

Table 1. Duncan's multi-range test results for mean ratings of professional sketches

Scene number	1a	1b	1c	1d	1e	1f	1g
Mean[a]	2.86	3.39	4.50	5.02	5.30	6.18	6.84

[a]Two means not underscored by the same line are significantly different at the 0.05 level. Two means underscored by the same line are not significantly different at the 0.05 level.

Based upon the ratings of slides of the professional sketch pairs and series, the conclusion is nonprofessionals exhibit the same preference rankings for landscape modifications as professional landscape architects. The raters in this study were exclusively university students and may not be representative of the public at large. However, given the magnitude of the differences between the ends of the seven-item series, it is highly unlikely that the general public would respond differently.

DISCUSSION

Given the results of this study, how might sketches be used to gather public input on proposed landscape modifications? The first task would be to prepare slides for presentation at a workshop. A series of slides representing proposed landscape modifications would be required. For a given modification, say a power line installation, two or three alternatives should be chosen for evaluation. The alternatives might include the most economical installation, an esthetically pleasing alternative (as judged by a professional landscape architect), and a compromise alternative. Several sketches should be made for each modification alternative. Each sketch should depict the alternative as viewed from a different perspective. Actual photographs and slides of sketches of the unmodified landscape should also be made from the same perspectives. By presenting several perspectives of the same scene, a more realistic and reliable measure of the public's reaction will be possible. This series of slides, presented in random order, should allow adequate ranking of the alternative modifications.

It would also be desirable to prepare approximately five sketch-photograph pairs expected to cover the complete range of the scenic beauty scale. These pairs would establish the regression line for predicting photograph ratings from sketch ratings. This set of actual photographs and slides of sketches intermixed with the slides of modification sketches would also help reduce any biased ratings of the modifications because of recall from one scene to another. The regression line would indicate whether public workshop participants generally rated the sketches lower than corresponding photographs as the raters did in our study. The extra sketch-photograph series spanning the scenic beauty scale would place the values for the proposed modifications on a scale that had its basis outside the study area. If the same extra series were used in a number of studies, the series could become a common reference scale to compare severity of modifications among different areas.

After the rating of randomized slides by workshop participants, data analysis similar to that performed in this study would be a simple matter. Comparison of the proposed modifications is straightforward given the regression line and the ratings for each modification. If an agency only wanted to compare ratings within one set of possible modifications and did not project to ratings after modification, it would not be necessary to establish a regression line.

One final note is necessary. Even if completely successful, this technique has the same characteristics as other public input techniques. That is, this technique will give decision-makers additional input, but it will not make decisions. Like letters, petitions, and questionnaires, the input from this technique must be weighted and judged. The primary advantage of using this technique is that esthetic evaluation can be incorporated with other technical evaluation data in the decisionmaking process.

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Papers from a workshop and symposium at the Ninth Annual Meeting of the Environmental Design Research Association discuss identifying environmental features responsible for perception of environmental quality, dimensions of wilderness experience, uses of wildlife, integrating user-based assessments with economic models, and the interface of natural and urban landscape elements.

Keywords: Amenity resource values, environmental quality, wilderness, wildlife, user-based assessments, economic modeling, urban landscape.

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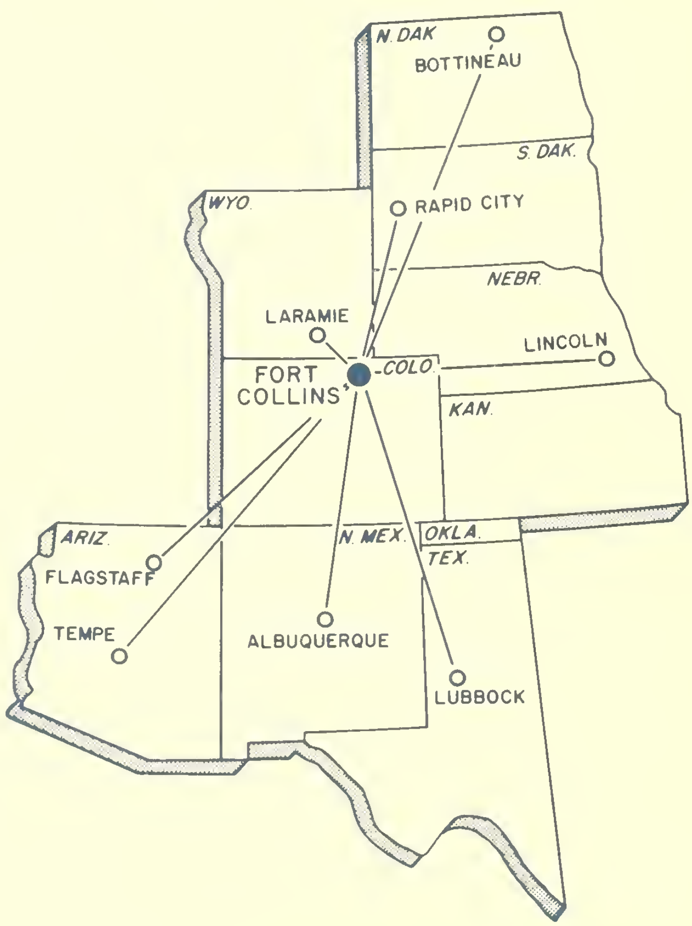
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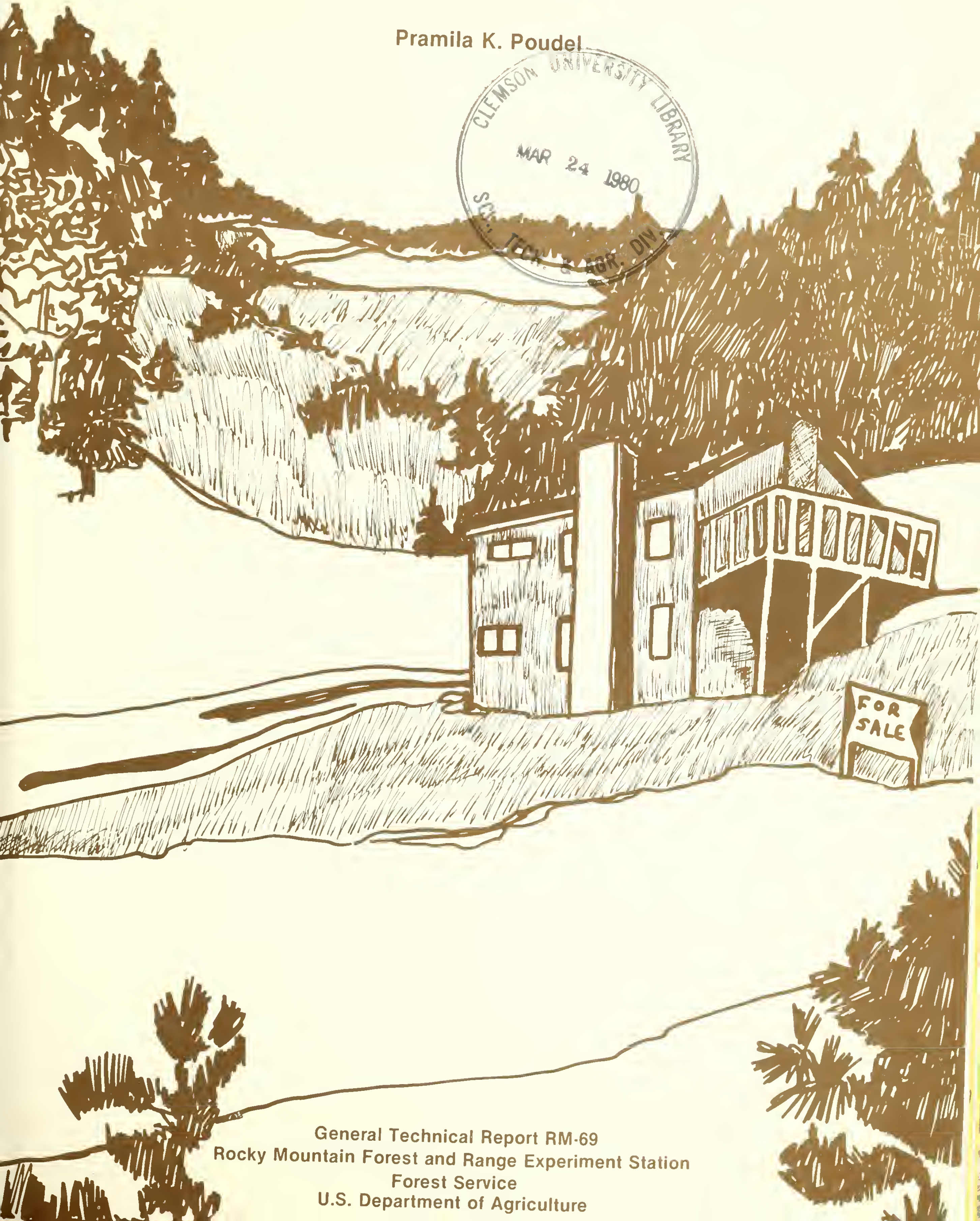

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Capitalization of Environmental Benefits into Property Values: Literature Review

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Abstract

The social benefits derived from public environment improvement projects are one important justification for increasing such projects. Economic theory predicts environmental benefits are capitalized as increased property values. This paper reviews several empirical studies which use differential property values to demonstrate this capitalization.

[1]Author is presently with the Range Management Staff Unit, National Forest System, Washington, D.C. The paper was prepared at the Station's Research Work Unit at Flagstaff, in cooperation with Northern Arizona University; Station's headquarters is at Fort Collins, in cooperation with Colorado State University.

Capitalization of Environmental Benefits Into Property Value: A Literature Review

Pramila K. Poudel

Total outlays for environmental concerns have increased by 210% since 1973 (Office of Management and Budget 1979). Since economic resources are limited, allocating them on the basis of sensible and consistent criteria of project worth has become increasingly important. Investment decisionmakers need measures which enable them to compare the benefit derived from spending equal numbers of dollars on vastly different projects.

Decisionmakers have received little guidance in selecting an appropriate appraisal method for evaluating projects. Consequently, public investment decisions about environmental programs often suffer from inadequate information about the economic benefit.

The focus of this study is only those public programs which involve improving residential attributes, (e.g., public parks, playgrounds, lakes, reservoirs, open space, air quality, and other environmental amenities). Such environmental amenities are preserved or developed because of the belief that natural environment and outdoor recreation help people build and maintain physical and psychological health (Frank 1962).

In a consumer-sovereign society, economic value is traditionally thought of in terms of utility to the users (consumers) and this utility is measured by money. So, consumers' willingness to pay for a product is thought to measure the value of a given product. In a competitive exchange economy, consumers' willingness to pay is assumed to be registered in the market price; therefore, the social value of that product is measured by the price the product would bring in the market.

Unfortunately, most of the environmental products, such as scenic beauty, open space, and clean air, are not usually traded in the market, even though they are deemed highly useful. Such goods are provided free; so there are no directly observable market prices which can be conveniently interpreted as the consumers' willingness to pay for such products. This sharply limits the possibility of actually measuring the benefits on the basis of market prices as one would be able to do in the case of tangible and marketed products, hence the need for developing indirect methods of measuring the dollar value of environmental benefits accrued from public projects.

Environmental Differential

Public programs, such as air pollution control and preserving a site as an amenity area, generally have locational impacts. Such programs provide differential geographical advantages by enhancing the utility of areas differently in terms of availability of or proximity to amenities. If consumers prefer to live near an area where such facilities are made available, they will be willing to offer a higher price for such property than for a similar property elsewhere. The price of otherwise comparable properties close to amenities would be bid up above the price of properties without such proximity to amenities. Thus a differential price will result depending on proximity to amenities.

The property price differential or "locational rent" resulting from proximity to environmental amenities may be interpreted as the value of the amenity. Consequently, the marginal value of a public environmental project can be measured in terms of the increase in land value in the vicinity of the environmental project.

The rate of property price or rent changes as proximity changes is known as rent gradient in economic literature. A considerable number of recent studies dealing with the measurement of the environmental benefits of public environmental projects have utilized the property value approach to estimate the consumers' demand price for environmental services.

Use of the property value procedure to estimate the gains from public environmental programs is based on the assumption that residential property prices reflect not just the structure and quality of building material embodied in the property, but also the surrounding subjective valuation which the buyer places on the property.

Capitalization Theory

When land is bought, what is being exchanged is an entitlement either to income from the property or to enjoyment of the land. A capital asset is being exchanged, the market price of which is based on the value of future net benefits that the asset is expected to generate. From a theoretical point of view, the value of any productive land roughly equals the sum of all its economic net benefits discounted back to the present. The capitalization formula of land value normally used in the computation of the land values is as follows:

$$V = \frac{R_1}{(1+r)} + \frac{R_2}{(1+r)^2} + \cdots + \frac{R n}{(1+e)^n} \qquad [1]$$

Expression [1] reduces to V = R/r as n approaches infinity, where V is the capitalized value of the property in terms of present worth, R_1 stands for the net income (or personal enjoyment) of the first year, R_2 for the net income (or personal enjoyment) of the second year, and so on, where each year's income is thought of as being received at the end of the year.

Suppose, for example, that a piece of property is expected to produce a net income (benefit) of $100 per year for an indefinite period of time, and the simple interest on alternative investment is r (say r = 0.05). What will be its price of capital value? The capital value, V, of $100 a year net earnings discounted back to the present at an annual rate R = 0.05 will simply be $100/0.05, or $2,000. If the present owner of this property has to sell, he will not rationally sell it for less than $2,000. But the amount which a potential buyer will pay for that property, will depend upon what he expects it to bring in net benefits. The present value of the flow of net benefits, compared with those obtainable from other assets, will set the upper limit.

It is not hard to see that different people might value the same piece of property differently. They might have different expectations about the size of the net benefits, or they might discount future earnings at different rates. For instance, people assign different values to a scenic view, the proximity to water, wooded land, a park, etc. While calculations of the present value of a property may differ, we can assume the market price of any actual sale must lie at or above the present value to the seller and at or below the present value to the buyer.

Now assume that a governmental agency decided to preserve for environmental and recreational purposes a large amenity area in the vicinity of that property. Further assume that the owner of the property and the investors (buyers) of the property visualize the forthcoming environmental benefits from the public program. If they do so, this newly visualized benefit would be capitalized in the market value of land near the project. As a result, land values in the neighborhood of the project will increase. If we assume that this particular environmental improvement scheme adds $100 in net benefits to the abovementioned property, the capital value would be ($100 + $100)/0.05 = $4,000 instead of $2,000 without the program. Whether the person owning that property sells it or holds it to personally enjoy the environmental improvement, he will have benefited from the public investment.

Focus of Paper

Environmental decisionmakers could apply the differential property price technique to measure the benefits of public environment projects if analysts have confidence in the ability of the approach to furnish useful information. If we are to believe that differential property prices can be used to estimate environmental benefits, we must find evidence that these benefits are in fact capitalized into property value. It is useful to review a large number of empirical studies that used this approach and examine them for evidence of such capitalization into property value.

Because it is cumbersome to concentrate on all problems at once, the main emphasis in this paper is to seek evidence of the capitalization of environmental benefits by reviewing empirical studies, rather than by examining the theoretical and methodological content.

Evidence of Residential Environmental Preferences

A considerable number of studies have attempted to develop a general model for the determination of the price of residential property. Within the framework of those models, the effect of specific dwelling attributes have been analyzed. From those studies some evidence of the capitalization of environmental attributes, such as parks, open space, lakes, etc., into residential prices has been developed.

This review consists of a brief summary of the empirical content of a number of studies done in the areas of (1) water resource development, (2) recreational projects such as state and neighborhood parks, (3) impact studies of open space preservation, and (4) air pollution.

Discussion for each group of studies will consist of a brief summary of the empirical works, followed by a discussion of several of the leading studies in each group, exploring in more detail their empirical results.

Water Resource Development Studies

There have been a number of studies on the impact of water-based developments on the value of lands near the developed area. In an early study, Knetsch (1964) attempted to develop a procedure for measuring the benefits of proposed or anticipated public investments in water resource development projects, especially benefits rising from the recreational potential. Knetsch's approach was to compare property values around an existing water-based recreation development with values in a similar area which did not possess such a development. He assumed the location advantage created by the project would be capitalized into surrounding land values and that the differences between land values in the areas with development and areas without development were caused by the investment.

Knetsch collected data on such variables as distance from reservoirs, topography, and urban proximity and related the variable to sale prices of individual parcels of land. He developed two regression equations, one for an area with a project and one for an area without. He found that land bordering a reservoir does have incremental value attributable to the development and concluded, based on his Tennessee Valley Authority data, that "If a reservoir were completed in 1963, the land is estimated to be valued at approximately \$4,265,000. Without the reservoir, the value of this land is estimated to be \$2,307,000; a difference in value attributable to the reservoir of \$1,958,000." With a discount rate of 4%, the average annual benefit is \$160,677.

David (1968) carried out a similar study in the Kissimmee River Basin in south-central Florida comparing residential lots with and without water frontage. She analyzed the effects of recreational water quality, topography, and other physical characteristics of an area on residential lot prices and found the proximity of water based recreation facilities is an important determinant of land values. As she expected, lots with water frontage commanded higher prices than similar lots without water frontage, providing a definite indication the benefits of water frontage were being capitalized into the sales value of residential lands.

David and Lord (1969), following upon David's earlier work and using the same procedures, found land bordering artificial lakes did have increased value attributable to the presence of water. Williams and Daniel (1969) found the most rapid increases in land values attributable to water developments occurred around the date project construction was announced. Significant increases in land values do not wait until the water-related benefits are actually available; rather values are capitalized based on anticipation.

Conner et al. (1973) attempted to determine the relationships of values of water frontage to other land value factors, especially structures. Prices for lots in the Kissimmee River Basin were estimated as a function of the year of sale, size of lot, and presence or absence of houses. It was found the presence of lake frontage contributed 65% of the total value of a typical vacant residential lot and 48% of the total value of lots having houses on them.

Similar but more limited studies carried out by Weiss et al. (1966), Kitchen and Hendon (1967), Mann and Mann (1968), and James (1968) tend to confirm these results.

The conclusions drawn from this research are that (1) land values rise in the vicinity of water-based recreational developments; (2) the rates of value increase are more rapid than for comparable areas without a reservoir, stream, or lake; and (3) the rates of value increase are most rapid shortly after the announcement of facility development. Thus, capitalization of future benefits occurs long before the benefits are received.

Employing data on individual dwelling units in a metropolitan area of Seattle, Wash., Brown and Pollaskowski (1977) attempted to estimate the economic contribution of proximity to water and water related open space (i.e., the land contiguous to water to which pubic has access and such areas are defined by the authors as set back) to value of single family residences.

The authors consider a housing unit as consisting of a bundle of attributes or characteristics which describe the structure itself, the land upon which it is built, and the location. The assumption was made that proximity to neighborhood amenities would describe the locational attribute of the housing bundle. As the neighborhood contained numerous bodies of water, with and without surrounding open space to which the public had access, the authors separated neighborhood amenities into two categories of variables; one was proximity to water and the other was the proximity to water-related open space with setback.

Widths of boundary areas were chosen to assure homogeneity in sample neighborhoods.

The open space variable employed was constructed by measuring the width of setback area

abutting the water and closest to the dwelling unit in question. The distance to the water front was measured as the shortest linear distance from the dwelling unit to the nearby water front.

The market prices of the dwelling unit sales transacted during the period of 1969-1974 were obtained from real estate sources. Estimates of the marginal implicit prices, or in simple terms, the marginal effect of each of the dwelling unit attributes, were obtained by regressing property price on the set of variables such as proximity to water front, setback size, lot size, living area, etc. Two different sets of regression equations, one for a lake area with setback and the other for two lake areas without setback, were used for analysis. The regression results in terms of "distance to water front with setback" and "distance to water without setback" variables were found to be significant at 0.99 level. The size of the setback variable was significant too.

The study concluded that a dwelling unit in an area close to a 200-foot-wide setback would sell for about $850 more than a comparable unit located near a 100-foot-wide setback area. The same dwelling unit, if located near a 300-foot-wide setback area, would sell for about $1,350 more than if located near a 100-foot-wide setback area. Thus, the benefits of waterfront were being capitalized in nearby property.

Park Related Studies

A number of studies have used the property value capitalization method to measure the benefits of neighborhood or other public parks. Kitchen and Hendon (1967) found that land value declined with distance from a park. A number of studies such as Weiss et al. (1966), Schutjer and Hallberg (1968), and Hammer et al. (1971) have concluded parks affect neighboring property values, implying benefits of the natural environment are being capitalized into property price.

Weicher and Zerbst (1973) applied a property value model similar to that used by Kitchen and Hendon on five parks in Columbus, Ohio. They concluded property facing a park would sell for 23% more, on the average, than identical properties elsewhere. Properties with a scenic view of the park would sell for about 10% more.

Schutjer and Hallberg (1968) attempted to evaluate the extent to which the per acre value of different types of properties located near a state park was affected by the development of the park. Taking observations on property transfers before and after the development of the park, Schutjer and Hallberg observed the influence of the park on land prices in the nearby area. In this study, the technique of measuring the benefits of a reservoir was to compare the surrounding land values before and after a project, as opposed to the Knetsch approach which employed simultaneous pricing of land with and without development of added amenities.

The authors used multiple regression analysis with 20 independent variables. Both topographical characteristics such as the slope and soil type of the land, and environmental variables such as the road distance in miles to the nearest park, were used as independent variables. A rural area of Pennsylvania was chosen as the study area. The basic data were based upon transfers of properties located near a 2,250-acre state park which is within 20 miles of two relatively large populated centers in Pennsylvania. Data were collected on 286 property transfers occurring during the period 1950-1965 in the township containing the park. These data were supplemented with information on property characteristics which were available from tax duplicates, aerial photographs, and soil surveys. Properties were classified into two groups: (1) properties containing less than two acres and (2) properties containing more than 2 acres. Each class was divided again into two types of properties, one with buildings and another without buildings. Thus, four equations were estimated. Their results showed sale price per acre was significantly influenced by the distance from the park.

Hammer et al. (1971) based their study on the assumption that all the benefits of a park, in terms of both scenery and direct accessibility, may be reflected in land values. In their statistical analysis they limited their observation to properties closer to the park than to any open space and not adjoining any retail areas or major highways. This minimized the variation in property value due to other real estate value generators. Thus, the study concentrated only on relatively homogeneous housing.

Houses were classified into 16 types to enable the separation by statistical means of the value components associated with house type from those associated with accessibility to parks.

Multiple regression was used to estimate the magnitude of the effect of proximity to the park on different types of houses. Effects were isolated by using two groups of dummy variables (i.e., one or zero variables): variables pertaining to house-type sets, and variables pertaining to the age of house at time of sale. In their model, the only independent variable present besides two groups of dummy variables was the distance to the park. Two forms of regression equations were employed, a linear form and a logarithmic form. The regression results in terms of the distance to park variable were found not signifi-

cant at the 0.05 level for the entire sample of 333 property sales. Since the magnitude of distance to the park from abutting properties was almost zero and the distance to the park from corner properties was arbitrarily measured, the authors concluded that those properties might have blurred the relationship between property price and distance variable; such properties were excluded in the regression analysis.

After 19 abutting properties and 11 corner properties were excluded from the sample, the distance variable was significant in both the linear and log forms. In order to get the locational rent, Horn and Coughlin subtracted a rough estimate of average house price from total property value, thus identifying land price. The value of the typical property, ($16,392) multiplied by 83.2% (constant for all properties in the study area), the average tax assessment for the sample property, gave an average house value of $13,638. Thus, the difference between them is the locational rent. Relative to total land value, locational rent due to the closeness of the park was found to be substantial. At 100 feet, it accounted for 35% of land value, at 1,000 feet for 11%, and at 25,000 feet for 5%.

These two empirical studies clearly indicate the existence of a park has a positive impact on surrounding land values, but the magnitude of the impact differs among types of residential properties.

Open Space Preservation Studies

There have been relatively few economic studies done to evaluate open space preservation as opposed to urbanization. One recent study done by Coughlin and Kawashima (1973) is worth discussing.

Coughlin and Kawashima attempted to measure the effect of open space on surrounding property values. They identified public open space with recreational facilities, private open space (i.e., large estates), and institutional open space (e.g., colleges, country clubs, etc.) and tested the hypothesis that open space maintained in an urban area has positive effects on adjacent property values.

Coughlin and Kawashima also attempted to find out whether the effect of open space could be seen in higher values of the buildings themselves which were located near open space. They thought that this could happen in two situations. One possible situation is that developers, consciously trying to capture the benefits of proximity to open space, may build larger and, therefore, more expensive houses on land adjacent to open space, intending to sell them to well-to-do buyers. The second possibility is that houses near open space may be of higher quality, though not larger, than houses far away. Therefore, the study was designed to explore two major questions: (1) do more expensive dwellings (including the value of land) tend to be found in locations with relatively high accessibility to open space, and (2) do higher quality (land value) dwellings tend to be found in such locations? In order to investigate these questions, the concept of accessibility of a given residential block to open space of a given type was identified. In order to give special attention to those blocks which adjoin or touch open space, a dummy variable was used. Four equations were estimated with different dependent variables. The four dependent variables were: (1) average value of owner-occupied housing unit on each block; (2) average value per room of owner-occupied housing unit on each block; (3) average contract rent of renter-occupied housing unit on each block; and (4) average contract rent per room of renter-occupied housing units on each block. Independent variables were accessibility to the types of open spaces and distance to the city in miles. The regressions were run in stepwise fashion.

From the regression result it was concluded that the accessibility to private and institutional open space was important for home owners. For renters, accessibility to public open space was important. The results of this analysis support the hypothesis that open space of various kinds has a positive effect on the capitalized and rental value of nearby properties.

The findings also support the hypothesis that both expensive and high quality dwellings are found in locations with relatively high accessibility to open space.

Furthermore, the study also attempted to estimate the magnitude of the effect of various sizes of hypothetical circular parks on the property value of the study area and the rent gradient generated by those different sizes of circular parks. The study area was divided into four rings, and the distance from the center of the park to residential properties into each ring was measured. The effects of different sizes of parks on properties in the four different rings were estimated. The results demonstrated the aggregate magnitude of the effect in the 0- to 1,000-foot ring of a 1-acre park was $171,400, the effect of a 5-acre park was $803,000, and effect of a 25-acre park was $3,485,000. Thus the study concluded that the marginal contribution of additional acres was substantial.

The magnitude of the contribution of a 1-acre park per dwelling unit was estimated at $83 in the 0- to 1,000-foot ring, $12.97 in the 1,000- to

2,500-foot ring, \$3.13 in the 2,500- to 5,000-foot ring, and \$0.83 in the 5,000- to 10,000-foot ring. The decreasing magnitude of the dwelling unit price difference in each of the four rings showed that the effect of a park was declining with the increases in distance from the park.

Air Pollution Studies

A number of studies have been undertaken to examine the relationship between air quality and house price. Studies of Anderson and Crocker (1971), Ridker and Henning (1967), and Strotz (1966) all conclude the effects of pollution are, to varying degrees, reflected in house prices.

The main purpose of Ridker and Henning's study (1967) was to examine whether air pollution externalities were reflected in house prices. The area of study was St. Louis, Mo., and 1960 census data were used for empirical investigation. Multiple regression was employed to estimate the relationship between house price and the following independent variables: air pollution index, housing density, population density, school quality, number of non-white people, and a set of house characteristic variables.

The results show that air quality is important and significant, and emphasize the negative effect of increasing pollution levels on property values. The authors estimated an increase of between \$83 and \$245 per site would result if pollution levels were cut back by 0.25 mg per 100 cm per day. The authors say the pollution variable is as important as the highway accessibility coefficient.

Summary and Conclusions

The results of this brief survey show that environmental preferences exist, and that environmental variables are significant determinants of property prices. This is so despite the fact that the measures of environmental characteristics used in various studies were quite different and were usually crude.

The empirical instances of environmental benefits being capitalized on property value found from the above reviewed literature indicate the benefits of public environmental programs can be measured through the differential property value method. Land values are affected by people's preference for proximity to a recreation area. Rent on land nearest an amenity has proven to be high, indicating individuals who locate near a site do enjoy the use and view of the area with little inconvenience. So the increment in land value near the public project area could be taken as the benefit of the site.

This method does not provide complete estimates of value when there are significant benefits outside the area nearest the public environment project. The property value approach is applicable only when there is a sufficient quantity of private properties being exchanged near the public project. The increase in property value due to a public project is an underestimation of the total gain from public projects, since environmental and recreational benefits are enjoyed by parties other than residential property owners. For example, when water or other recreation areas are developed by public investment, many other businesses such as building trades, retail businesses, grocery stores, sporting goods suppliers, and the like may also benefit. All these secondary effects of public investment are not estimated through the property value method. Therefore, the method provides a lower bound (minimum) estimate of the benefits of public environment projects (Lind 1973). A further problem which Lind considers in more detail is a possible discrepancy between land value and net benefits. The market for land may be such that not all changes in business profit and consumer's benefits can be captured in land values. However, it is also possible that if a number of similar activities are competing for each parcel of land, the land value change will capture the benefits of competing activities also. Separating which projects or activities contributed to the change in land values would be difficult.

The house price studies reviewed in this study provide some evidence of the capitalization of the benefits of environmental services into property values, but the evidence is not enough to suggest which specific kind of environmental goods consumers perceive as environmental amenities. The missing feature in past research is the absence of a theory which is adequate to explain consumer's residential choice behavior in terms of environmental variables. Future studies should fill this gap. Incorporation of an appropriate econometric model into a theoretical framework is required to pinpoint the effect of specific environmental attributes on property prices.

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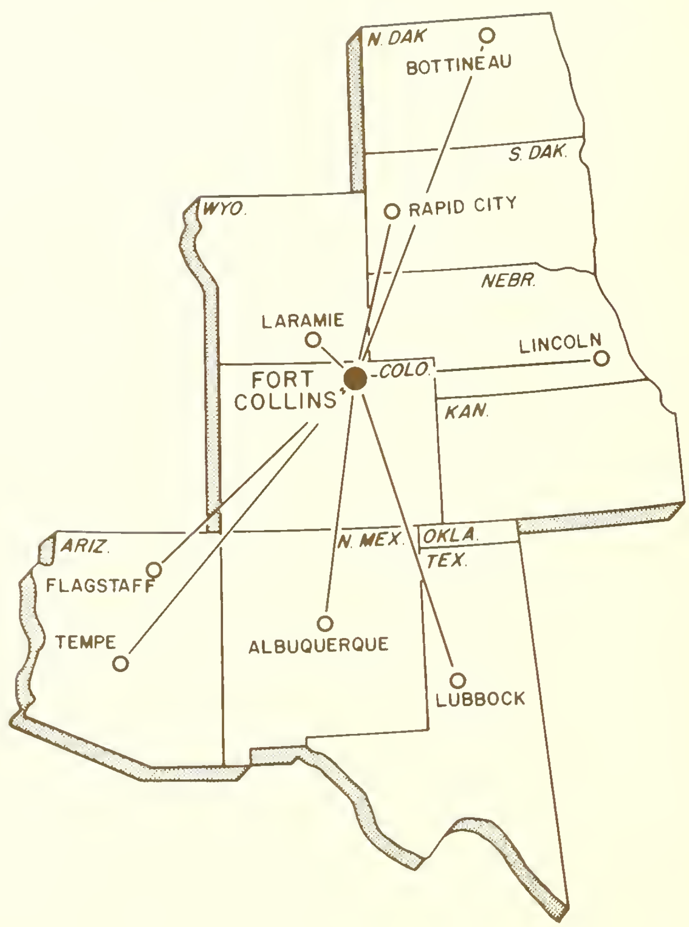
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Deer in Arizona and New Mexico: Their Ecology and a Theory Explaining Recent Population Decreases

Henry L. Short

General Technical Report RM-70
Rocky Mountain Forest and
Range Experiment Station
Forest Service
U. S. Department of Agriculture

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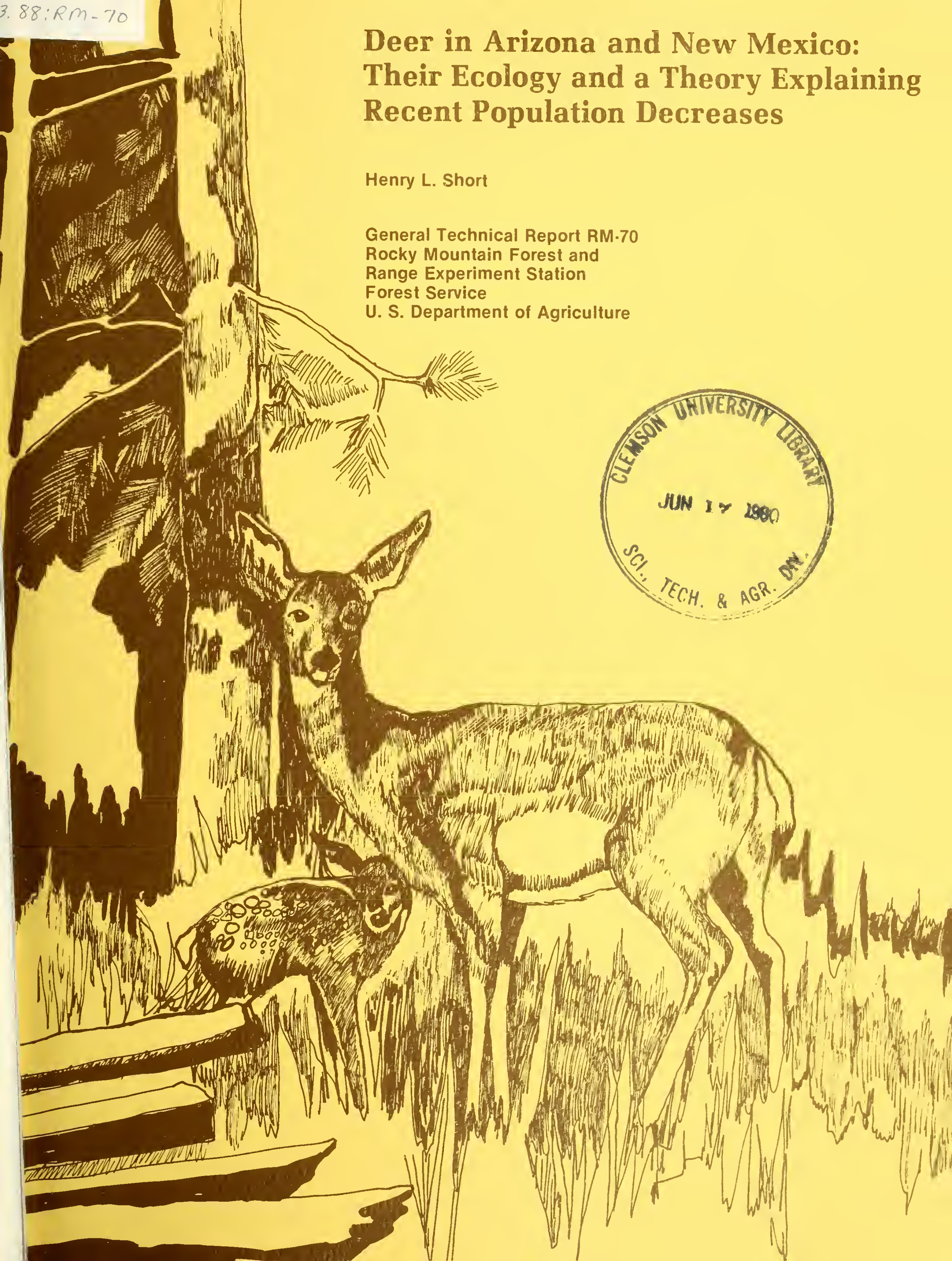

Abstract

The hypothesis that declines in southwestern deer populations from late 1950's levels have been caused by relatively low fawn recruitment rates (because of habitat quality) combined with increased female mortality (because of antlerless deer hunting) is supported by computer simulations of the dynamics of southwestern deer herds.

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SUGGESTIONS FOR DEER MANAGEMENT IN THE SOUTHWEST

Data Gathering Techniques

Accurate information about the population structure of deer herds is essential to effective management of the resource. Quantitative information about deer in many areas of the Southwest is difficult to obtain because deer managers are dealing with large, often inaccessible areas with limited deer and hunter populations. Still, quantitative information is so important in terms of gaining insight about herd structure that great effort should be expended to gather relevant data. The data, if wisely used in computer simulations, can alert the deer manager to trends in herd populations or potential responses to proposed hunting options in time to prevent range problems or decimated herds.

Deer managers often rely on three types of field-collected information in order to assess their resource—large scale surveys of deer indicators, biological check stations, and actual observations of deer. In practice, the deer manager in the Southwest routinely has had little quantitative information upon which to base his herd management decisions.

The information available from large-scale surveys of deer indicators, such as pellet group counts and deer forage surveys, varies in quantity and quality for the different deer herds of the Southwest. At best, however, procedures such as counting pellet groups only indicate population trends, are subject to the vagaries of weather, and provide no information about the sex-age structure of a deer herd.

Game managers in the Southwest rarely get substantial biological information from biological check stations during the hunting season. For example, the New Mexico Game and Fish Department collected incisor teeth (to determine the age structure of harvested deer) at check stations in only 4 of 57 game management units in 1974. Only limited collections of incisor teeth, field dressed weights, and antler measurements were made in Arizona during 1974. Some useful sex-age information about deer herds can be obtained from check stations, since most human contact with deer occurs during the hunting season. Ovarian information yielding estimates of fawn production, herd age structure, and physical condition of does can be assessed if does are harvested. Estimates can be made of the size of the deer herd, and trends in herd populations can be suggested from data relating buck or deer kill to measures of hunting effort. Analyses of the age structure of killed deer, coupled with suitable computer simulations, can indicate whether survival of particular age classes such as fawns or yearlings is adequate or low.

Managers with both the New Mexico and Arizona Game and Fish Departments seem to rely on surveys of fawn:doe ratios after hunting season as a biological indicator of the structure and productivity of deer herds. Such surveys are generally accomplished by driving designated routes in as consistent a manner as possible between years to reduce sampling bias. Climatic conditions, deer behavior, and human workloads may greatly affect the number of deer observed. Useful estimates of trends in doe populations are probably not obtained. Fawn:doe ratios can be quite useful, however, if these data are supplemented by information about the survival rates of different age-classes of deer.

Deer herds in the Southwest were at relatively high levels in the late 1950's and declined until the late 1960's, apparently because of low fawn recruitment rates and the increased mortality of adult does caused by the hunting of antlerless deer. Lack of precise biological information about deer productivity and survival caused deer managers to inadvertently overlook trends in deer populations. It seems unfortunate that the quality of biological information presently being gathered in the Southwest may not allow present deer managers to be any more perceptive about trends in their statewide deer herds.

Management Strategies

Because deer productivity in the Southwest may be fundamentally limited by nutritional factors apparently associated with seasonal precipitation, deer management may be limited to optimizing useful vegetation in deer habitats,

minimizing herbivore competition, minimizing controllable sources of mortality, and harvesting highly productive deer herds in different ways from herds with low productivity.

Overgrazing by domestic herbivores in all vegetation zones can be deleterious to deer; enforcing grazing allotments at legitimate carrying capacity is a necessary management tool. Feral herbivores, such as wild burros, should be controlled when they are numerous enough to destroy vegetation needed by deer or to foul water catchments essential to wildlife. Predator control measures are justified if it can be demonstrated that wild carnivores adversely affect deer numbers and if herds are not already at range carrying capacity.

Continued urbanization has an adverse impact on deer. Unrestricted land development around cities and towns causes rapid deterioration of habitat. Mining activity, increased recreational use of public lands, and disturbances by off-road vehicles may also be detrimental to deer. Deer herds using Indian reservations as part of their range are difficult for state game and fish agencies to manage because the state agencies have no jurisdiction over the deer harvest and little input into habitat manipulation.

Some of the vegetation manipulation done on southwestern ranges to increase deer-carrying capacity has been found wanting. The cabling or chaining of large tracts in pinyon-juniper woodlands is expensive management. Benefits in terms of increased domestic herbivore production and water conservation frequently do not equal the cost of the woodland conversion (Clary et al. 1974). Furthermore, large block clearing of woodlands is detrimental to deer and elk (Short et al. 1977). Control of pinyon-juniper woodlands, done on a localized, prescription basis, can be beneficial; numerous small clearings are useful in areas of heavy wildlife use and where a dense tree overstory has reduced midstory shrub and understory forage production.

Browse production can sometimes be dramatically improved with prescription cutting. The proper seeding of browse, forbs, and grasses used as deer food can increase the abundance and variety of foods available to deer. Controlled burning or wildfires in dense pinyon-juniper woodlands can kill the overstory and contribute to an enriched grass and forb understory but may also destroy the valuable shrub midstory (McCulloch 1969).

Browse species in the chaparral brushlands may produce abundant crown sprouts following fire. This new growth is succulent, high in nutrients, and heavily used by deer (Swank 1956a). The increased nutritive value is lost several years after burning. Control of chaparral may provide a broader selection of foods and an increased midwinter supply of green forbs for deer, but control should not be extensive enough to destroy habitat by depleting available cover (Cable 1975).

Small clear-cuts, reseeded and interspersed with montane conifers, improve the vegetative composition and total forage quality (Neff 1974). Several studies have indicated the increased forage production and deer use which follows the disturbance or cutting of mature stands of trees (e.g., Patton 1969, Reynolds 1962). Vegetation manipulation to encourage the production of new growth in aspen stands improves deer habitat in subalpine forests (Reynolds 1969).

Manipulating blocks of forest and woodlands to provide a diverse plant community and increased production of foodstuffs is good deer management. Restricting competition from other herbivores, minimizing the disturbance of urbanization, and utilizing special environmental aids, such as watering areas, all have favorable impacts on southwestern deer. The situation remains, however, that the most favorable deer habitats in Arizona and New Mexico cover only about one-third of the land area and that precipitation patterns may modify the absolute productivity of some of these lands.

INTRODUCTION

Hunting antlerless deer has been used to control deer populations when deer herds have exceeded range-carrying capacity, and to provide an additional hunting resource when populations and reproductive successes are high and hunter demand is great. Deer populations can be sustained with limited hunting of antlerless deer under conditions of high fawn productivity, good fawn survival, and carefully prescribed rates of hunting mortality. Too often the hunting of antlerless deer has been applied to herds where fawn production and survival rates are unknown and where hunting mortality has not been carefully monitored. This occurred in New Mexico and Arizona in the late 1950's and 1960's. The resulting declines in deer populations were of greater magnitude and of greater duration than anticipated. Computer simulations of population growth assuming various survival rates for fawns, does, and bucks support the theory that hunting antlerless deer can produce drastically different long-term population effects in different herds.

As theorized, younger does in many portions of the Southwest bear relatively few fawns. In addition, only modest proportions of all fawns seem to survive to enter fawn-producing age classes. The ultimate cause of these limited rates of deer production is hypothesized to be the nutritional quality of forages which results from the soils and climate of the region. The important resource limitations suggested in this paper must be considered for statewide deer herd management programs to be successful.

The first part of this paper suggests tactics for managing deer in the Southwest. The second portion contains an analysis of the quality of deer habitats in the Southwest and an analysis of productivity and population dynamics of southwestern deer. The last part is a strategy for using the hunting of anterless deer to control herd population.

DEER OF THE SOUTHWEST

Distribution

There are four subspecies of deer of the genus *Odocoileus* in New Mexico and Arizona. About 90% of the total deer numbers may be mule deer (*O. hemionus*), with the remainder white-tails (*O. virginianus*). The few whitetails in eastern and central New Mexico belong to the subspecies *O. v. texanus* (Lang 1957, Hoffmeister 1962). The Sonoran or Coues whitetail (*O. v. couesi*) occupies suitable habitat in localized areas of southwestern New Mexico and southern and central Arizona (Hall and Kelson 1959). Arizona has perhaps 32,000 whitetails (Wilcox 1977), which may be three times the number found in New Mexico.

The desert mule deer (*O. h. crooki*) occupies chaparral and pinyon-juniper woodlands and the desert flatlands in the southern one-third of New Mexico (Lang 1957) and chaparral and desert scrub ranges from west central to southeastern Arizona (Hoffmeister 1962). The Rocky Mountain mule deer (*O. h. hemionus*) occupy mountain ranges and mesas in the northern two-thirds of New Mexico and a broad area north of a line from northwestern to east-central Arizona. Its range is generally delineated by the extension of pinyon-juniper growth into grasslands and brushy draws. Summer ranges extend from above timberline to foothills and valleys, and winter range extends to lower elevations depending on weather conditions. There are perhaps 150,000 mule deer in Arizona (Wilcox 1977) and 270,000 mule deer in New Mexico.

Deer are unevenly distributed in both states (fig. 1). Deer in Arizona are generally concentrated in the northern Kaibab, Mogollon Rim, White Mountains, and central and southeastern mountains; deer in New Mexico are concentrated in south central, northern, and southwestern game management units.

Habitat and Nutrition

Arizona and New Mexico contain varied habitats that are extensions of the Rocky Mountains, Great Plains, and the Great Basin of the United States and of the Sierra Madre Occidentals, the Chihuahuan Desert, and the Sonoran Desert of Mexico.

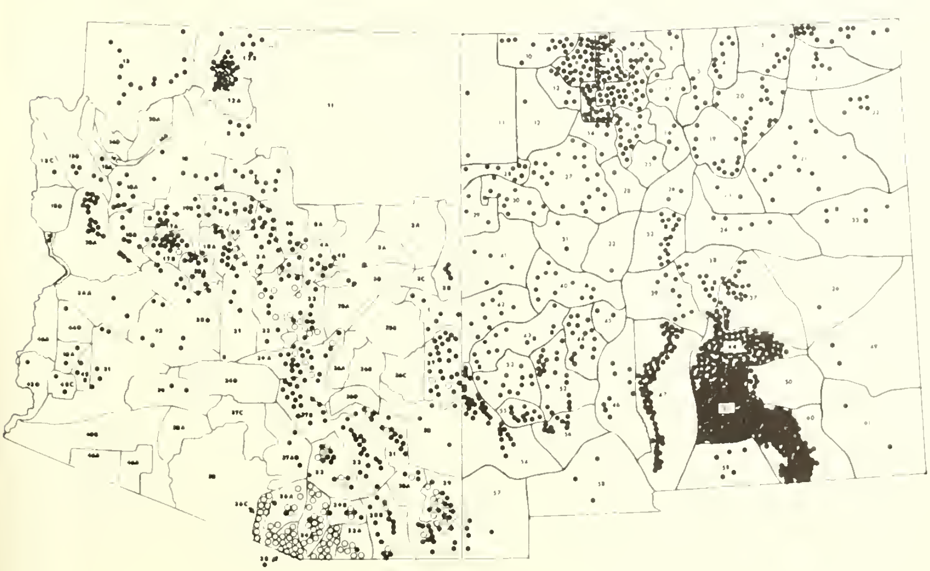

Figure 1.—Rate of deer kill in Arizona and New Mexico varies by game management unit. Each symbol represents 25 deer legally killed in 1974. For Arizona, large circles represent buck white-tailed deer, and small dots represent female mule deer killed on the north Kaibab. Large dots in both states represent buck mule deer. Game management units 11, 25, and 26 in Arizona consist of major Indian reservations.

There is, across these varied habitats, an important association between seasonal and annual aridity, soil mineral content, and forage quality. Low forage quality can routinely occur within forages on many southwestern deer habitats, and these deficiencies can adversely affect southwestern deer herds by lowering fecundity, fawn survival, and recruitment. The resulting low productivity seems characteristic of many southwestern deer herds.

Vegetation

Description

Areas where deer kill is greatest are presumably a function, among other things, of the size of deer populations and habitat quality. Buck deer kill during 1975 in the individual game management units in Arizona and New Mexico was regressed on the square miles of the different vegetation types within those game management units and compared with the distribution of those major vegetation types within the two states (fig. 2). Results of the regression analysis (table 1) suggest the deer population is concentrated in the following vegetation types: interior chaparral, madrean evergreen woodland (oak woodland communities), great basin conifer woodlands (pinyon-juniper communities), and petran montane conifer forest (ponderosa pine). These woodland and forest communities important to deer occur on about one-third of the land area of both Arizona and New Mexico (table 2).

Table 1.—The relationship of total mule deer buck kill (1975) and the area of each of the vegetation communities present within each different game management unit listed in the order in which the different habitat vegetation types were entered into significant multiple regression equations. Each variable below increased the R^2 value by at least 2%

Variable	R^2 value
Arizona	
Interior chaparral	0.18
Madrean evergreen woodland (oak communities)	0.26
Petran montane (ponderosa pine) conifer forest	0.34
Great Basin conifer woodland (pinyon-juniper communities)	0.37
Chihuahuan desertscrub	0.39
Petran subalpine conifer forest (spruce-fir)	0.41
New Mexico	
Interior chaparral	0.25
Great basin conifer woodlands (pinyon-juniper communities)	0.31
Petran montane (ponderosa pine) conifer forest	0.35
Madrean evergreen woodland (oak communities)	0.38

Nutrition

Studies of the food habits of mule deer and white-tailed deer in the Southwest indicate deer consume a great variety of plant materials (table A1). Other food habit studies will undoubtedly extend this list. Deer depend on perennial woody shrubs and trees for leaves, buds, succulent twigs, and fruit. Hardened twigs of limited nutritional value may be eaten during periods of environmental stress when other, more palatable foodstuffs

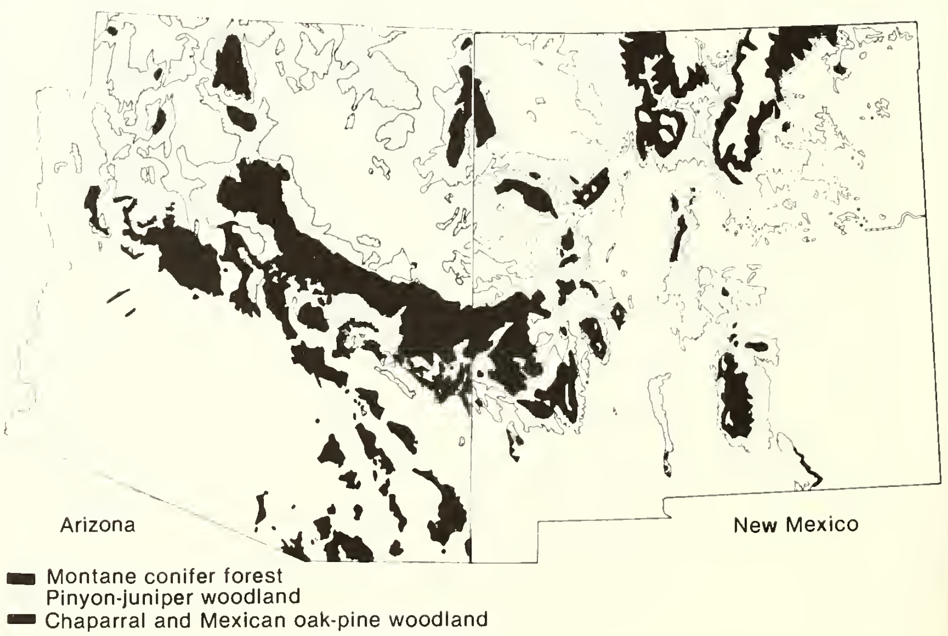

Figure 2.—Distribution of biotic communities in Arizona and New Mexico that comprise important deer habitat. Montane conifer forest equals the Petran montane conifer forest (ponderosa pine), pinyon-juniper woodland equals the great basin conifer woodland, and chaparral and Mexican oak-pine woodland equals interior chaparral and madrean evergreen woodlands listed in tables 1 and 2.

Table 2.—Approximate percent composition (to nearest 0.5% of the total land area) of vegetative communities in Arizona and New Mexico. Values estimated from map prepared by Brown et al. (1977)

Biotic communities	Arizona	New Mexico
Chihuahuan desertscrub	1.5	8.5
Sonoran desertscrub-lower		
Colorado River subdivision	17.0	0
Arizona Upland subdivision	14.0	0
Mohave desertscrub	4.5	0
Great Basin desertscrub	6.5	1.5
Semidesert grassland	8.0	21.0
Plains and Great Basin grassland	15.5	35.5
Interior chaparral	4.0	0
Madrean evergreen woodland	3.0	1.0
Great basin conifer woodland (pinyon-juniper)	18.0	20.5
Petran montane conifer forest (ponderosa pine)	7.5	9.0
Petran subalpine conifer forest (spruce-fir)	0.5	3.0
Alpine tundras	0	0
Subalpine grassland	0	0
	100.0	100.0

are unavailable. Deer seasonally eat forbs, mushrooms, fruits, nuts, and some green grass.

Leaves of woody plants frequently comprise the most important dietary item for deer across seasons in a variety of habitats (table A2). Forbs are seasonally important in winter and spring in chaparral-desert habitat, in summer in ponderosa pine habitats, and in spring and summer in semidesert grasslands and pinyon-juniper habitats. Cactus fruits are a significant portion of the autumn and winter diet of mule deer in semidesert grasslands (Short 1977).

A few nutritional studies have been accomplished with southwestern deer to help explain the observed fluctuations in deer numbers. The crude protein, phosphorus, and in vitro dry matter digestibility values for 25 forage samples composited to duplicate the seasonal diet of deer from several ranges are listed in table 3. The letters F (fair) and P (poor) appear after nutrient values lower than those cited as desirable by Urness (1973). White-tailed deer in chaparral habitats are dependent on forage of only fair digestibility from May to September, of only fair phosphorus content from July to January, and of only fair protein levels from July to September. Mule deer habitats frequently provide forage of only fair-poor phosphorus content throughout much of the year. Forage digestibility is only fair in chaparral and desert grassland habitats from October to December. Digestibility is only fair from July to September and poor from January to March in pinyon-juniper habitats. Forage protein levels for mule deer in pinyon-juniper habitats are only fair from July to December. Forages deficient in

Table 3.—Some nutritional values: percent crude protein, phosphorus, and in vitro dry matter digestibility of forages similar to those in ruminal contents of deer collected at the different seasons from different habitats. The letters F and P after a value indicate that value is only of fair or poor quality as suggested by standards listed by Urness (1973, p. 41). The brackets indicate months represented in seasonal data.

	Habitat type	Authority	Factor	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
White-tailed deer	Chaparral	Urness (1971)	Protein	11		13			12		9 F		12		10
			phosphorus	0.23 F		0.31			0.28		0.22 F		0.21 F		0.22 F
			digestibility	42		52			35 F		37 F		57		47
Mule deer	Chaparral and desert grassland	Urness (1971)	Protein	11		13			12		14		12		10
			phosphorus	0.21 F		0.29			0.25		0.23 F		0.26		0.16 F
			digestibility	40		51			43		42		35 F		34 F
Mule deer	Ponderosa pine	Urness (1975)	Protein					25	17	16	14	10			
			phosphorus					0.48	0.24 F	0.19 F	0.19 F	0.24 F			
			digestibility					68	54	56	46	49			
Mule deer	Desert grassland	Short (1977)	Protein	10 F			10				10 F		10		
			phosphorus	0.15 P			0.23 F				0.16 P		0.15 P		
			digestibility	54			52				48		45		
Mule deer	Pinyon-juniper	Boeker et al. (1972)	Protein		12			11			9 F			9 F	
			phosphorus		0.19 F			0.26			0.17 F			0.18 F	
			digestibility		23 P			45			37 F			43	

phosphorus are especially deleterious to deer since insufficient dietary phosphorus causes decreased inorganic blood phosphorus levels, depleted mineral content in bones, diminished rate of weight gain and milk production, and a possible reduction in animal fertility (Church 1971). Diets of low protein content cause slow physical development and low reproductive success in deer (Verme and Ullrey 1972).

Soils

Description

The vegetative types most associated with deer in New Mexico and Arizona generally overlay the mesic semiarid (mean annual soil temperature 8-15° C and annual precipitation of 25-41 cm) and the mesic subhumid and frigid subhumid soils (mean soil temperature less than 15° C and precipitation greater than 41 cm) (fig. 3, table 3). These soils tend to occur at higher altitudes and are characterized by being fairly well developed, leached, and acid (Maker et al. 1974). These soils types occur on about 32-35% of the land area of Arizona and New Mexico (table 4).

Influences on Nutrition

The nutrient quality of plants is directly affected by the nutrient content of the soil (Laycock and Price 1970). Soil moisture available for plant growth, which can affect both yield and chemical composition, varies extensively in Arizona and New Mexico (figs. 4 and 5).

Table 4.—Approximate area (ha) of major soil types in Arizona and New Mexico. Data after Maker et al. (1974) and estimated from the supplement to Arizona General Soils Map (U.S. Department of Agriculture 1975)

Soil types	Arizona	New Mexico
Light colored soils of warm desertic region (hyperthermic arid, thermic arid, and thermic semiarid)	16,521,700	8,002,400
Light colored soils of cool desertic region (mesic arid)	3,569,800	1,147,700
Moderately dark colored soils of uplands (mesic semiarid)	5,339,900	6,008,900
Moderately dark and dark colored soils of the mountainous region (mesic subhumid and frigid subhumid)	4,071,200	5,142,500
Moderately dark colored soils of east central plains	0	7,609,100
Dark and moderately dark colored soils of high plains	0	3,192,600
Total	29,502,600	31,103,200

The warm, dry climates with long, hot summers, common to 16,500,000 ha in Arizona and 8,000,000 ha in New Mexico, facilitate the oxidation of organic and inorganic materials from the light-colored soils. Soils become low in organic material and soil aggregates are frequently coated with iron oxides (U. S. Department of Agriculture 1964). These soils tend to accumulate thick horizons of calcium carbonate, and high levels of calcium, aluminum, or iron in the soil diminish the availability of phosphorus to plants, even when soil phosphorus is present (Reed 1973).

Total nitrogen in arid and semi-arid soils is inversely related to mean temperature (Jenny 1928). Very low levels of nitrogen are present in warm desert and semi-desert soils (Stevenson 1965). The nitrogen content of soils tends to increase as temperature decreases and precipitation increases in the transition from desert to mountains. Soils on north-facing slopes may have a higher nitrogen content than soils on south-facing slopes (Stevenson 1965). Vegetation growing on these wetter montane habitats would presumably have higher nitrogen values. Deer forage collected from ponderosa pine habitats during summer tends to have higher crude protein contents than forage collected from drier habitats (table 4).

Plants in early stages of growth have a high protoplasm/structural components ratio and the ability to store a variety of nitrogen compounds for future use (Viets 1965). During later developmental stages, the nitrogen is transported from leaves and stems into developing seeds or storage roots. Plants growing where soil nitrogen is deficient tend to have more carbohydrate production in above-ground tissues. When deficiencies are especially severe, no seed production occurs (Viets 1965). If only enough nitrogen is available for seed production, foliage eaters will be adversely affected because seeds accumulate nitrogen at the expense of other plant parts.

Precipitation Patterns

Description

The areas most heavily populated with deer tend to be areas with greater precipitation, lower evapotranspiration rates, and decreased soil moisture deficits. These climatic characteristics are illustrated in figures 4 and 5 for a variety of Arizona and New Mexico locations. Soil moisture deficits presumably reflect potential water stress for plants. Water stress, in turn, affects nearly every aspect of growth (Kramer 1969) including anatomy, morphology, physiology, and biochemis-

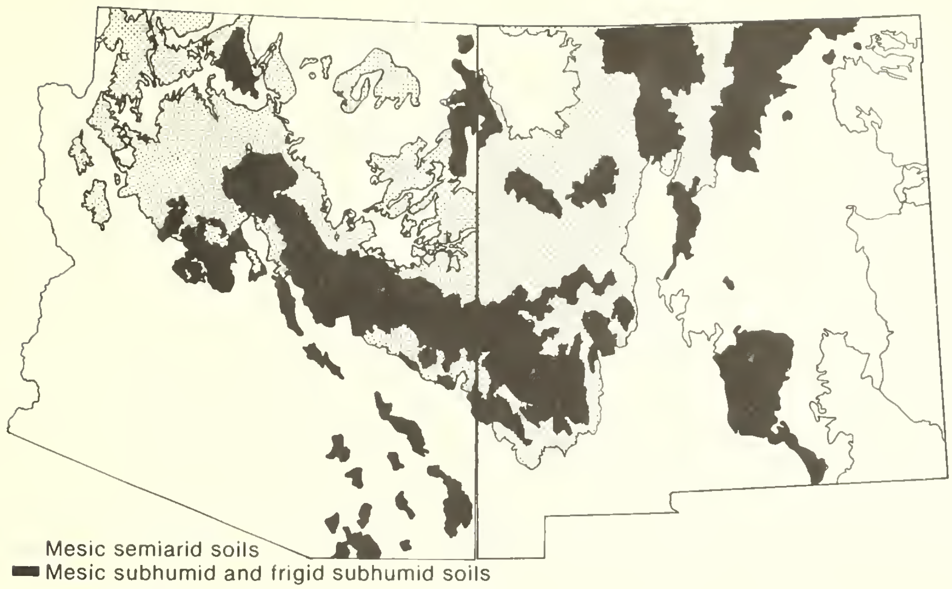

Figure 3.—Distribution of the major soil groupings occurring in important deer habitats in Arizona and New Mexico.

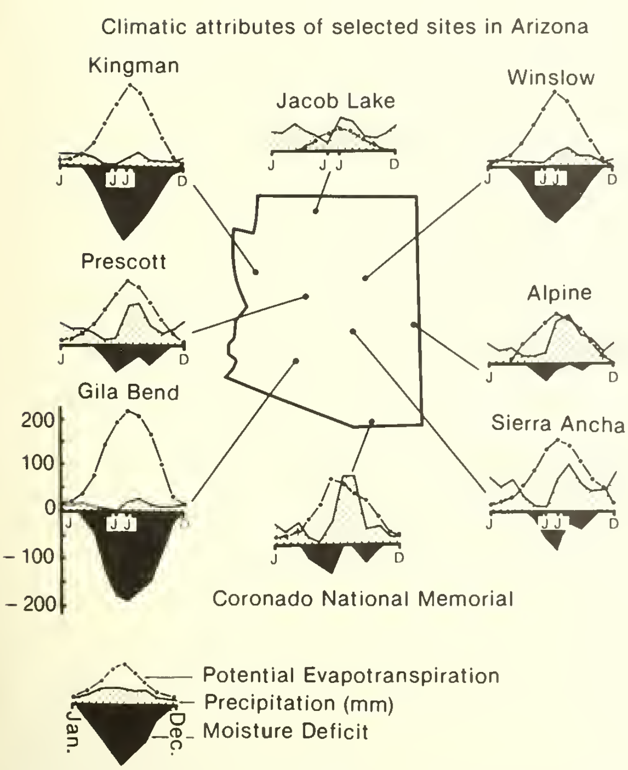

Figure 4.—Climatic characteristics of selected Arizona sites (after procedures in Thornwaite and Mather 1957).

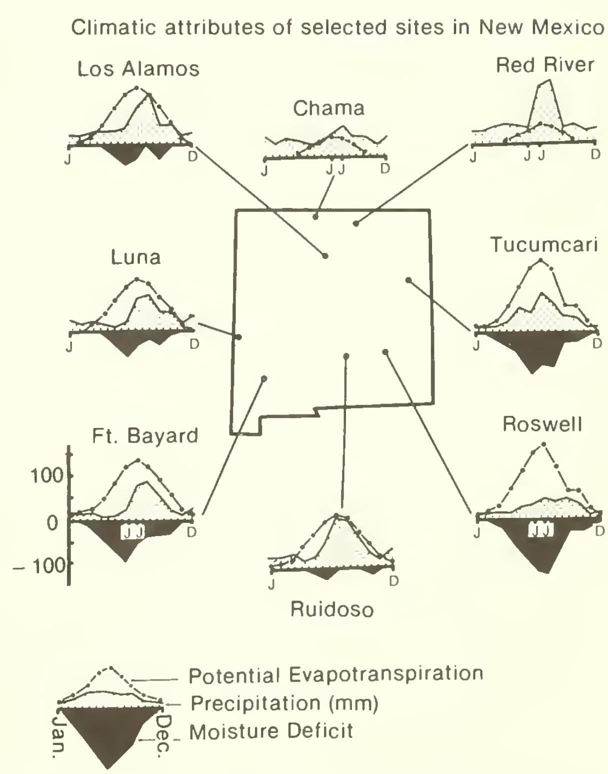

Figure 5.—Climatic characteristics of selected New Mexico sites (after procedures in Thornwaite and Mather 1957).

try. These changes, in turn, affect the seasonal presence, quantity, nutritional quality, and palatibility of food plants.

The non-winter months are critical to deer throughout the Southwest because of the combined deleterious effects of seasonal droughts and elevated temperatures on vegetation. Severe winter weather, on the other hand, is confined to high mountain ranges and can be avoided with seasonal moves by deer to lower elevations where the extensive woodlands provide necessary food and cover.

Patterns of seasonal precipitation vary throughout Arizona and New Mexico (figs. 4 and 5). Precipitation is highest in the summer and lowest in winter in eastern New Mexico and highest in summer and lowest in spring in southwestern New Mexico. The spring drought in Arizona is progressively more severe in the central and western portions of the state and at lower elevations (fig. 6).

The routinely severe spring drought which occurs over much of Arizona may be an important influence on the quality of deer habitat in that state, especially in comparison to north-central and south-central New Mexico. Spring and summer soil moisture deficiencies, more extensive in Arizona than New Mexico (figs. 4 and 5), may affect the quality of deer habitat to an even greater degree when they follow winters of limited precipitation.

Seasonal precipitation affects forage production in the Southwest and consequently influences deer production. Summer precipitaiton affects the production of annual and perennial grasses, mushroom growth, and the regrowth of shrub tissues during the critical production season for deer (fig. 7). Numerous studies have emphasized the vulnerability of the neonate fawn and the importance of adequate nutrition for the doe to increase the likelihood of fawn survival during parturition, lactation, and weaning. In Arizona and New Mexico only subalpine and montane coniferous habitats have precipitation rates which exceed potential evapotranspiration during this critical season.

Autumn and winter precipitation affects the production of cool season annuals and perennials (fig. 7), especially in elevations below 1,800 m. During these seasons, deer consume succulent forbs and grasses, in addition to making heavy use of evergreen browse (table A1). Autumn and winter are seasons of maintenance for deer in general—conception and early gestation for does, post-weaning stress and growth for fawns, and rut for bucks (fig. 7).

Adequate spring moisture is necessary for good shrub growth, subsequent fruit production on woody plants, and the production of annual and perennial grasses and forbs (fig. 7). This is a critical production period for southwestern deer, with does recovering from the stress of winter and needing adequate nutrition to ensure successful parturition (Verme 1962). For surviving fawns, spring is both a recovery period and a time of growth and development; for bucks, spring is a recovery period and a time of antler regenesis.

Influence on Nutrition

Soil moisture is often abundant early in the growing season when herbaceous plants have high nutritive quality and grow rapidly. As soil moisture diminishes and temperatures increase, herbaceous plants mature and dry and nutritive value falls.

The forage values of different plant types are similar at the inception of growth but vary with continuing growth. Forage is high in nutrients such as carotene, phosphorus, and crude protein during initial growth and for some time thereafter. The ratios of leaf tissue to other plant tissue usually diminish with maturity. Coincidentally, carotene, phosphorus, and crude protein levels and digestible energy become reduced, and fiber levels increase.

Shrub tissues generally retain high carotene values throughout the year, while carotene contents in grasses and forbs decline to very low levels with plant maturity. Digestible proteins in shrubs, forbs, and grasses all decline with maturity. Levels common to mature forbs and grasses may be inadequate for maintenance of deer. The phosphorus content of grasses is generally deficient after seed formation (Cook 1972). Phosphorus deficiencies are so common in mature grasses on western ranges that supplements are recommended to maximize livestock production. In xeric habitats plants mature more quickly, producing less dry matter and nutrient deficiencies that occur sooner and last longer. Leaching of mature or dry herbaceous tissues by rain often causes large decreases in protein, phosphorus, ash, and carotene contents. Some leaching of nutrients and minerals may also occur from growing vegetation (Laycock and Price 1970).

POPULATION DYNAMICS

Deer herds on the xeric ranges of the Southwest may have an inherently lower productivity rate than herds in other areas of the West. Few experimental studies of deer productivity in Arizona and New Mexico have documented this

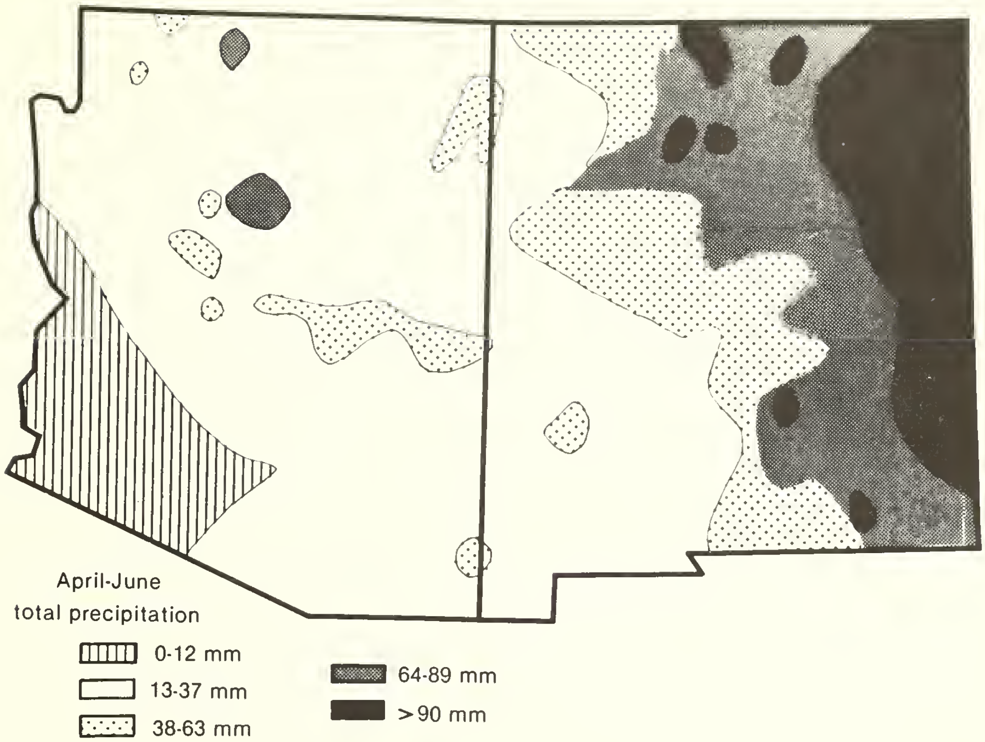

Figure 6.—Spring precipitation patterns in Arizona and New Mexico.

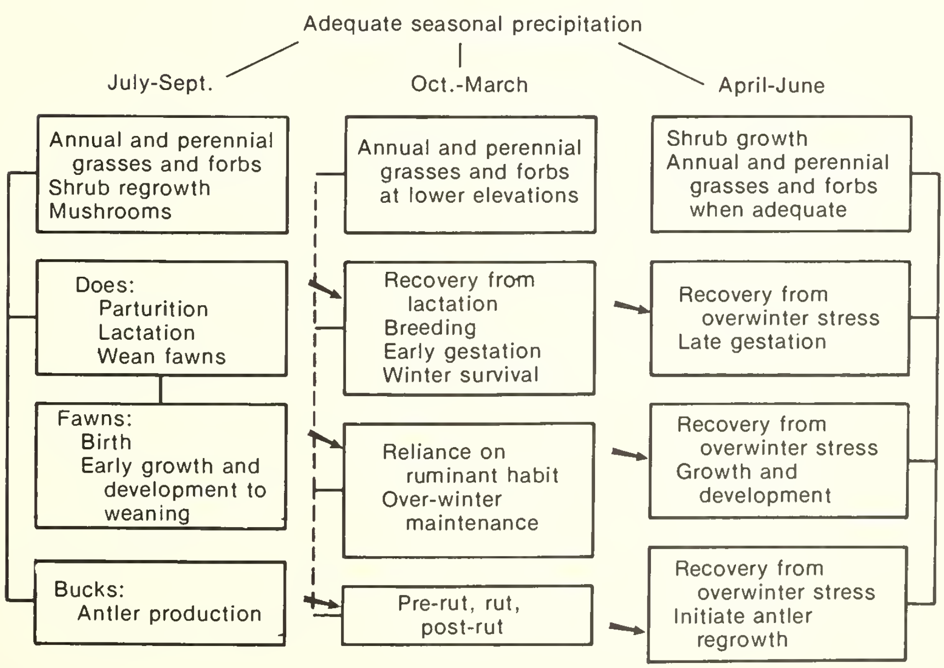

Figure 7.—The relationship of seasonal precipitation and deer production in the southwest.

generalization, so the routine analysis of production rates in different herds would immeasurably aid the understanding of deer herd dynamics in the Southwest.

Measuring Production

Information from Reproductive Tracts

Production rates of white-tailed deer in Arizona, mule deer in Arizona and New Mexico, and mule deer in Utah have been estimated from data gathered since the 1950's largely by personnel of the state game and fish departments. These data are presented in table A3.

Reproductive tracts were examined from does whose ages were estimated by tooth eruption and wear patterns. Ovaries were collected and later examined for corpora albicantia, ductless glands developed within the ovary by the reorganization of the Graffian follicle following ovulation. This count is a liberal estimate of the numer of embryos implanted, which, in turn, is a liberal estimate of the number of fawns born.

Corpora albicantia occur only rarely in 1-1/2-year-old mule deer, from Arizona and New Mexico, indicating almost no natality for 1-year-old does. Counts of corpora albicantia from 27-month-old mule deer does from north and south Kaibab, Mingus Mountain, and the Guadalupe Mountains indicate that 2-year-old does in these areas average less than one fawn. In general, corpora albicantia counts in 3- to 5-year-old mule deer does suggest these deer provide substantial recruitment into the deer herd but average fewer fawns per doe than older, more mature females.

Data for white-tailed deer in the Southwest are limited and not differentiated by doe age classes. The average number of corpora albicantia per doe was about unity, and Day (1960) states that there was no evidence of reproductive activity in female fawns. There is no evidence among these limited data that white-tailed deer in the Southwest will experience the explosive herd increases which sometimes occur in other parts of the country.

Data obtained for good mule deer ranges in Utah include number of fetuses per doe, a more conservative production estimate than corpora albicantia counts. Robinette et al. (1955) reported that doe reproductive tracts containing 792 corpora albicantia yielded 708 fetuses. Doe fawns from Utah, like those in Arizona and New Mexico, produced essentially no fawns. Does on these ranges 1-1/2 years old, however, averaged more than one fetus per doe, and 2-1/2-year-old does produced fetuses at a rate indistinguishable from older females.

Deer production data can be expressed in terms of potential reproductive performance during the doe's first 5 years of life. Mule deer does producing corpora albicantia at the rates observed in the Guadalupe Mountains potentially provide only two-thirds as many fawns in their first 5 years of life as does reproducing at the rate observed for Utah deer. Does from north and south Kaibab and Moqui ranges of Arizona would produce 75, 85, and 92% as many fawns in their first 5 years as Utah does. Differences in fawn survival rates between habitats could further modify these potential recruitment rates.

Interpreting Fawn:Doe Ratios

The ratio of fawns to does is routinely calculated in Arizona and New Mexico from extensive deer surveys conducted in late autumn-early winter following hunting season.

High fawn:doe ratios are presumed to indicate good deer herd recruitment (good production and/or high survival rates) and an increasing resource. Fawn:doe ratios, however, do not necessarily reflect production and survival of fawns. With 100% fawn survival, such widely divergent fawn:doe ratios as 0.25 and 1.25 could be due only to the age structure of the doe population.

A herd of 10% 1-1/2-year-old does that did not breed as fawns, 20% 2-1/2-year-old does averaging one fawn at 24 months of age, and 70% 3-1/2-year-old or older does that had an average of 1.5 fawns per doe the previous summer could provide a fawn:doe ratio of 1.25. A doe population of 80% 1-1/2-year-old does, 10% 2-1/2-year-old does, and 10% older does would yield a ratio of only 0.25. Both populations could increase appreciably in subsequent years if survival rates of yearlings and mature does were high. Thus fawn:doe ratios do not, by themselves, provide enough useful information for predicting population trends.

The proportion of fawns to does varies with the survival rates of fawns, yearlings, and adult does. Table A4 is a computer simulation designed to determine population trends when different doe age classes survive at different rates. Trends are indicated by computing the doe population (yearling and older) after 10 years as a percent of the original doe population. Fawn:doe ratios are dependent on both the age structure of the doe population which determines the numbers of fawns born and the survival rate of the fawns. Fawn survival rates of 80% can yield fawn:doe ratios of 0.70-1.04; survival rates of 60% can

yield ratios of 0.60-0.80; survival rates of 40% can yield ratios of 0.44-0.55; and 20% survival rates can yield ratios only up to 0.28. The highest fawn:doe ratios for a particular rate of fawn survival occur when yearling survival is lowest (i.e., the non-producing doe age class is removed from the calculation). When fawn and yearling survival rates remain unchanged, the fawn:doe ratios vary with the survival rate of mature does and its effect on fawn production. This is indicated in the following discussion.

A fawn:doe ratio of 0.81 occurs when fawn and yearling survival rates are 80% and adult survival rate is 90% (table A4). Under these conditions, the doe population after 10 years is 901% of the original. A fawn:doe ratio of 0.82 occurs when the survival rates of fawns, yearlings, and adults are 80%, 60%, and 70%, respectively, and the doe population is nearly unchanged after 10 years. With fawn survival of 60%, yearling survival of 20%, and adult doe survival of 90% (fawn:doe ratio of 0.80), the doe population after 10 years will be only 75% of the original population. When fawn survival is 70%, yearling survival is 40%, and the survival of adult does is 70%, the fawn:doe ratio is 0.79; but after 10 years the doe population would only be 29% of the original number. Obviously the fawn:doe ratio becomes a meaningful indicator of deer herd population trends only when the survival rates of the various age classes are also known.

Fawn:Doe Ratios in the Southwest

Fawn:doe ratios have been determined on a statewide basis in Arizona since about 1956. The statewide ratios from 1956 to 1964 seemed low (0.42), an occurrence which, if real, might be associated with the effects of climate on habitat quality. Long-term variations in southwestern climate are suggested in figure 8 with tree ring data from 46 sites in Arizona and New Mexico. Tree ring data are summarized by 5-year periods from 1900 to 1964 as the percent of sites with tree ring widths less than 90% of normal. Tree ring data have not yet been summarized for the years following 1964. Patterns in tree ring widths reflect past variations in moisture and temperature which have the ability to limit growth processes within the tree (Fritts 1966). Reduced precipitation affects soil moisture and subsequently the water balance of the tree. High temperatures increase rates of evapotranspiration, respiration, and photosynthesis which can adversely affect both the production of forbs and leaf, bud, and fruit development on perennial

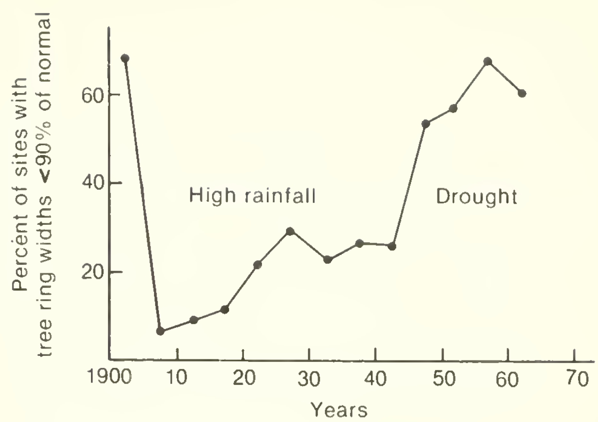

Figure 8.—Tree ring data indicate an extensive drought in Arizona and New Mexico during the mid-twentieth century.

woody species. These foodstuffs are important to deer since their presence influences the condition of does during mid and late gestation which can affect the survival of neonatal fawns and subsequent recruitment into the deer herd (fig. 7).

Tree ring records in figure 8 indicate drought conditions from 1900 to 1904, mesic conditions from 1905 to 1920, followed by generally declining precipitation until 1945. An extensive drought period occurred from 1945 to 1964. The apparently low (0.42) Arizona fawn:doe ratios were determined during the last 9 years of this period. Increasing impact of civilization and hunting pressure in the Southwest unfortunately coincided with these unfavorable climatic conditions and this period of apparent limited deer productivity.

Fawn:doe ratios also vary by habitat type within a state. In Arizona, ratios for the north Kaibab and some southeastern game management units were significantly higher ($P < 0.05$) from 1956 to 1973 than were ratios for several central basin game management units. Portions of the forest and woodland areas of north-central and south-central New Mexico also seem to have higher fawn:doe ratios than other game management units in that state.

Survival Rates and Deer Herd Dynamics

There are 84 combinations—seven rates of fawn survival, four rates of yearling survival, and three rates of survival for mature does—represented in the simulations in table A4. Only 17 of the 84 combinations simulated for 10 years yielded doe populations that were at least 105% of the original doe population. Only six combina-

tions of survival rates yielded populations equal to 95-105% of the original population. Sixty-one of the 84 simulations reflect combinations of survival rates insufficient to maintain doe populations through 10 years with the fawn production rates utilized in these simulations. These results (figs. 9 and 10) indicate that herds like those simulated in the exercise increase only when the survival rates of adult does are high (90%) or when fawn and yearling survival rates are moderate to high (70-80%), and the survival rate of adult does is moderate (70%). Doe populations remain stable after 10 years when fawn and yearling survival rates are either moderate (60%) or high (80%) and doe survival rate is moderate (70%). Stable populations also occur when the adult doe survival rate is high (90%) and the survival rates of fawns and yearlings vary from low to high in several combinations.

The doe population decreases over time in about one-third of the simulations with high adult doe survival rates (because the fawn and yearling survival rates are low) in 85% of the simulations with moderate adult doe survival rates, and in all the simulations with a low adult doe survival rate (50%).

The most important variable in maintaining a deer population may be the survival rate of the adult does because they are the reproductively active segment of the herd. For the conditions of these simulations, any environmental pressure, including the shooting of does, that increases adult doe mortality will cause a decrease in herd numbers. If recruitment rates are limited, doe survival rates must be high in order to prevent a drastic decline in deer numbers.

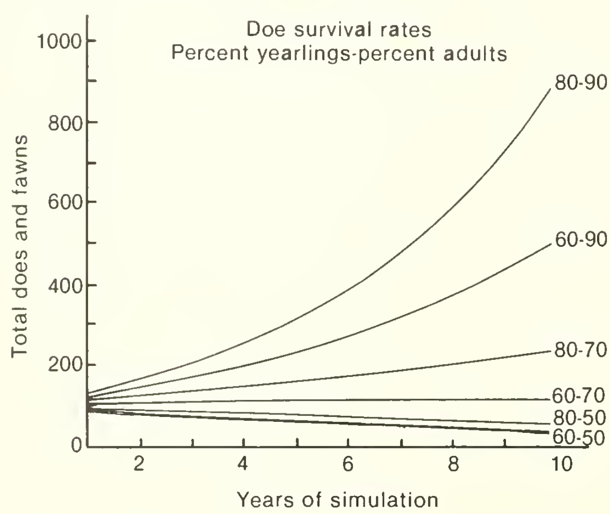

Figure 9.—Simulated changes in doe populations over 10 years when fawn survival rate is 80% and yearling and adult doe survival rates vary, part 1.

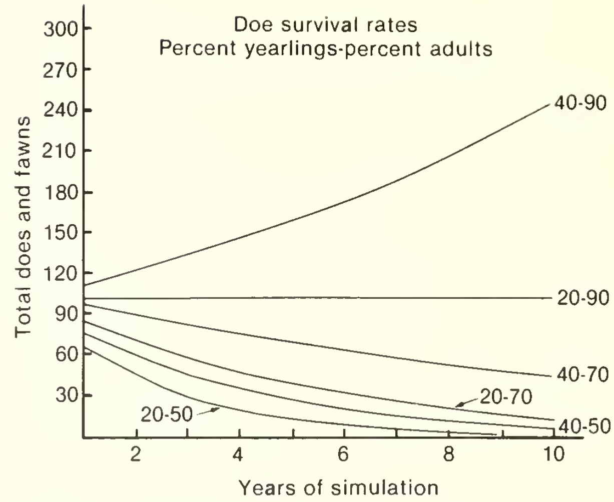

Figure 10.—Simulated changes in doe populations over 10 years when fawn survival rate is 80% and yearling and adult doe survival rates vary, part 2. Note change in ordinate scale from that in figure 9.

Midwest White-tailed Deer Population Simulation

The George Reserve, a 1200-acre fenced tract in southern Michigan, was stocked with two bucks and four does in March 1928. Counts in December 1933 indicated a population of 160 deer (Chase and Jenkins 1962). The eruptive productivity of the George Reserve herd has become legendary, and some subsequent deer management policies have been based on the assumption that the potential for recovery of deer numbers will quickly compensate for any errors of commitment.

It is difficult to simulate the growth of the George Reserve herd because the productivity of the individual age classes is not known. Sufficient information is available for some simulations to be made about productivity in the white-tailed deer herd in the Crab Orchard Wildlife Refuge in southern Illinois in order to develop baseline information. Productivity rates on the Crab Orchard Refuge (40 fawns:100 1-year-old does, 170 fawns:100 2-year-old does, and 185 fawns:100 older does; Roseberry and Klimstra 1970) are not as high as those apparently present on the George Reserve.

In the following simulation very high survival rates of 90% for 1-year-old does, 95% for adult does, 80% for 1-year-old bucks, and 85% for adult bucks have been used. The high survival rates are assumed to reflect the reduced mortality present within a fenced enclosure. The survival rate for the fawn crop was varied from 50% to 80% in the simulation. Expected herd in-

creases through 6 simulated years are presented in figure 11.

Central Arizona Mule Deer Population Simulation

A 600-acre deer enclosure on the Three Bar Wildlife Management Area near Roosevelt Lake in the central basins of Arizona was stocked in 1970 with three mule deer bucks, five does, and two fawns. Six years of data from the enclosure were available for the simulation presented in figure 11. Survival rates used for mule deer were the same as for the Crab Orchard white-tailed deer, and the usual productivity rate for mule deer in the Southwest of 100 fawns:100 2-year-old does and 150 fawns:100 adult does was used. Fawn survival for mule deer was varied from 40% to 80%. It is obvious from figure 11 that even when the survival of white-tailed fawns in a highly productive herd is only 50%, deer numbers increase at a greater rate than do southwestern mule deer herds with fawn survival rates as high as 80%.

The deer enclosure at Three Bar was constructed and stocked in order to determine the "natural rate of increase" for mule deer in the central basins, an area of apparently limited recruitment. If yearling and adult survival rates used in the simulation are similar to those actually occurring within the Three Bar enclosure, then observed deer numbers most nearly resemble that simulation curve in figure 11 with a fawn survival of 50%. Fawn survival outside the Three Bar enclosure may be even lower, suggesting that the central basins are an area where deer recruitment is quite limited.

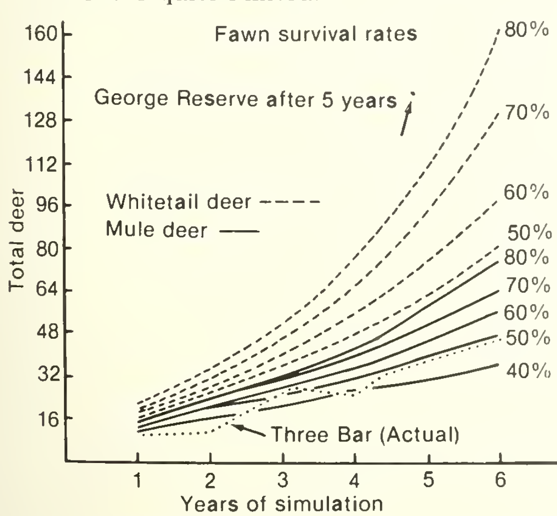

Figure 11.—Simulated rate of increase for a mid-western white-tailed deer herd and a southwestern mule deer herd. The observed rate of increase in the Three Bar deer enclosure is also indicated.

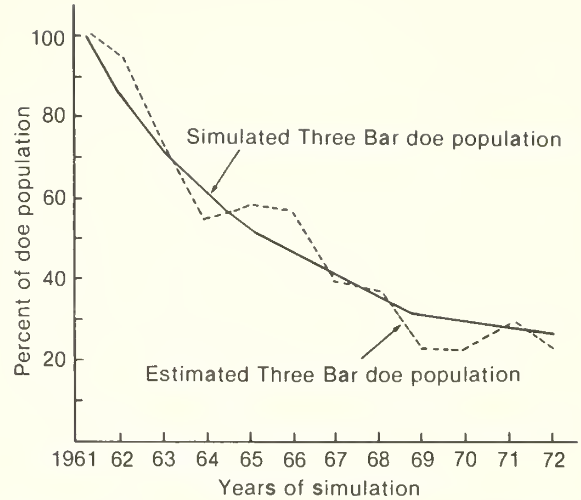

Figure 12.—Simulated versus observed changes in the deer population of the Three Bar Wildlife Management area in central Arizona.

After a simulated 6 years, the mule deer herd with a fawn survival rate of 80% was less than one-half the size of the white-tailed deer herd (fig. 11). It seems clear that harvesting tenets developed for eruptive white-tailed deer populations are not applicable to southwestern deer herds where fawn production, fawn survival, and herd recruitment rates are low.

The Three Bar deer herd can be used as an example of the consequences of using common management techniques when herd recruitment is low. The total Three Bar Wildlife Area consists of about 61 square miles of cattle-free deer habitat (Smith et al. 1969), 45 square miles of which are mule deer habitat. Estimates of the approximate size of the mule deer herd were made periodically from 1961 to 1972 from large scale pellet group surveys converted to approximate deer numbers. Buck:doe and fawn:doe ratios were determined by surveys in late autumn or early winter following the hunting season. These ratios were used in the simulation in figure 12. The observed fawn:doe ratio suggests a recruitment rate of about 30%. At this recruitment level doe populations increase slowly with 80% yearling survival and 90% adult doe survival (table A4) and remain unchanged with 80% yearling survival and 85% adult doe survival. The Three Bar deer herd was assumed to be static before antlerless deer hunting occurred; so survival rates of 80% and 85% for yearling and adult does were used in the simulation to reflect the condition prior to antlerless deer hunting.

There were about 700 does in the Three Bar herd in 1961 (Le Count 1974) when "heavy" antlerless deer hunting commenced. After 4 years

of "heavy" hunting (1961-1964), the doe population was only 400. Four years of "light" hunting (1965-1968) followed, and the doe population was further reduced to 200 (Le Count 1974). The total Three Bar mule deer population during this 8-year period dropped from 1300 to 300 animals.

After 4 additional years of buck-only hunting, the doe population was unchanged. The simulation in figure 12 assumes that legal kill and crippling of does from 1961 to 1964 ("heavy" antlerless deer hunting) increased doe mortality 15%, reducing yearling survival to 65%, and adult doe survival to 70%. The "light" antlerless deer hunting from 1965 to 1968 is assumed to have increased doe mortality 10%, thus reducing yearling survival to 70% and adult doe survival to 75%. These mortality rates are somewhat greater than those estimated for the same data by Smith et al. (1969). Yearling survival of 80% and adult doe survival of 85% were assumed for 1969-1972 when buck-only hunting occurred. It is obvious the greatest impact on the Three Bar deer herd was not the 350-400 does harvested over the 8-year period but the 3500-4000 fawns lost to the herd over the 12-year period because of the overall reduction in the doe population.

Northern Arizona Mule Deer Population Simulation

Another example of the apparent effect of antlerless deer hunting in areas with low recruitment is evident in northern Arizona, although the fluctuations in the regional deer herd are not as well documented as those for the Three Bar deer herd. Overuse of some Arizona deer ranges was obvious in the 1940's, apparently due to an increasing deer population following 40 years of adequate precipitation (fig. 8) and generally low harvests of the statewide deer herd by a limited hunting public. Tree ring data (fig. 8) indicate the late 1940's, 1950's, and early 1960's comprised the most extensive drought period of this century in the Southwest. By the latter half of this period, deer populations were relatively high, carrying capacities reduced, and there were some deer die-offs; for example, on the north Kaibab (Swank 1958). Deer recruitment during this period was low, and an extensive compilation of late autumn-early winter fawn:doe ratios indicated a ratio of only 40 fawns:100 does for Rocky Mountain mule deer. This ratio is achieved when a fawn survival rate of about 35% occurs.

Limited hunting of antlerless deer outside of the north Kaibab was first allowed in Arizona in 1949 (Jantzen 1964), and the extent of antlerless hunting gradually increased through 1952, increased substantially through 1958, and de-

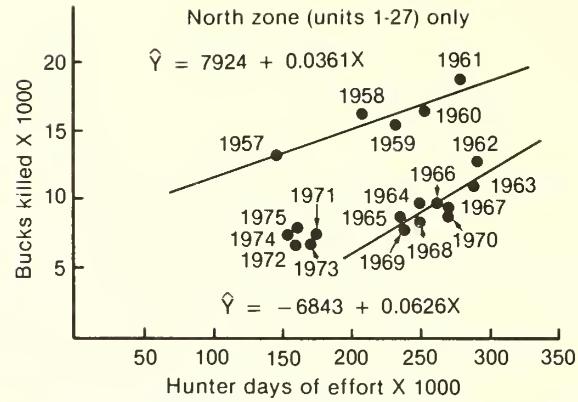

Figure 13.—Hunter effort required to kill buck mule deer in Arizona.

creased gradually through 1963. About 75,000 antlerless deer were harvested in northern Arizona (game management units 1-27) from 1952 to 1963 (Jantzen 1964). From the late 1950's until 1961 the antlerless deer kill was greatest and the buck kill gradually increased in proportion to increased hunting effort (fig. 13). Any residual buck population from years of underharvest, as well as the annual yield of buck deer, was being harvested. The buck kill in 1962 was only two-thirds that of 1961, even though hunting pressure remained constant. Buck kill per unit of effort was significantly less from 1962 to 1970 than from the late 1950's to 1961 ($P < 0.05$), presumably because the sustained yield of bucks was significantly diminished. It appears that this occurred because the productive doe population had been reduced critically by annual hunts of antlerless deer, even though that harvest had seemingly occurred at a modest rate.

The relationship between even modest increases in the mortality rates of does over an extended period and the decreasing mule deer herd in northern Arizona is further illustrated in figure 14. The simulated population originally contained 100 does (20 1-year old does, 40 2-year-old does, and 40 3-year-old or older does) that produced 100 fawns the first July. Values plotted represent deer numbers in January after the usual fawn mortality. Data from Rocky Mountain mule deer in northern Arizona would represent some multiple of these values. From 1956 to 1964 state personnel observed buck:doe:fawn ratios in late autumn and early winter of 35:100:42 in game management units 1-27. This fawn:doe ratio is achieved when a survival rate of about 35% occurs. A deer herd will sustain itself at this low level of recruitment only with high survival rates (e.g., 70-80% for yearling does and 85% for adult does). The first 5 years simulated in figure 14 correspond to the early 1950's when deer popu-

lations were at high levels and either slowly increasing or static. Survival rates were about 35% for fawns, 80% for yearling does, 60% for yearling bucks, 85% for adult does, and 65% for adult bucks. Years 6-15 of the simulations in figure 14 represent the period about from 1954 to 1963 when antlerless deer hunting was allowed and doe survival rates were consequently diminished. Years 15-25 are recovery years, when buck-only hunting occurred.

The 5% added doe mortality in figure 14 is probably a conservative estimate of the effect of antlerless deer hunting during a decade when the total legal antlerless deer kill in northern Arizona was over 68,000 (Jantzen 1964). After a simulated 10 years at this decreased doe survival rate, the deer population is only 60% of the original, suggesting that by the mid 1960's the northern Arizona deer herd could have been reduced by about 40%. The simulation indicates a buck:doe:fawn ratio little changed at 31:100:41.

The observed fawn:doe ratio in northern Arizona from 1965 to 1974 was 48:100. This ratio is achieved when a fawn survival rate of about 40% occurs. This fawn survival rate was incorporated into the simulation for the last 10 years. Survival rates for the other age classes remained the same as during the first 5 years of the simulation. After a simulated 25 years, corresponding to the mid 1970's, the deer population had slowly increased to about 80% of the fifth year (mid 1950's) level. Simulated buck:doe:fawn ratios were 38:100:46. Surveys done in the mid 1970's produced ratios of 27:100:48. This would indicate actual buck mortality was even greater than that reflected by the simulation.

Figure 14 also represents the population simulation realized if antlerless deer hunting during years 6-15 increased doe mortality by 10% instead of 5%. After a simulated 10 years of

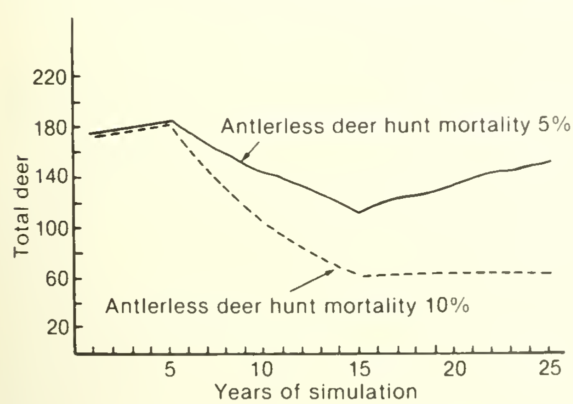

Figure 14.—Simulated changes in the Rocky Mountain mule deer herd of northern Arizona in relationship to the increased doe mortality resulting from antlerless deer hunting.

antlerless deer hunting, the deer population would be only 33% of the original. Little increase in the total population would be realized after 10 years of recovery.

The simulations presented in figure 14 may offer a plausible explanation for the general changes in Arizona deer populations for the 20 years from the mid 1950's to the mid 1970's.

THE HUNTING OF ANTLERLESS DEER AS A MANAGEMENT TOOL

It is obvious that any decrease in the survival rates of fawn-producing age classes will effectively reduce a deer population. It is difficult to consider the hunting of antlerless deer in herds with limited recruitment as acceptable deer management, except as an isolated effort to reduce herds to range-carrying capacity. Although the killing of antlerless deer under conditions of limited recruitment provides some short-term recreational hunting, it may well be at the long-term expense of the deer herd.

The hunting of antlerless deer can be utilized to maintain deer population at desired levels when herd recruitment is high and herds are at range-carrying capacity.

The north Kaibab in Arizona represents a relatively rare management opportunity in the western United States. This legendary range comprises about 526,000 ha of which 162,000 ha are summer range (Russo 1970).

The north Kaibab deer herd presents game management personnel the opportunity to either maximize the harvest of the resource or concentrate on harvesting a very high quality product (i.e., the trophy buck). The forage, nutrients, and energy required to produce a trophy quality, mature buck are much greater than those required to produce a yearling buck (Short 1972). The decision concerning which management scheme to pursue requires an impressive understanding of the deer herd. Requiring hunters with permits for hunting antlerless deer to harvest only antlerless deer and restricting the number of bucks killed would tend to keep total deer numbers in check while yielding a long-age-structured buck population. High fees could be charged for permits to kill trophy bucks produced under these management conditions.

Hunting antlerless deer can, theoretically, maintain total deer numbers and still yield a relatively high proportion of trophy bucks when deer production rates are high. A deer herd that originally consists of 35 bucks, 100 does, and 100 fawns with 70% fawn survival will vary in size

Table 5.—The effect of different doe and buck survival rates (percent) on the production of trophy bucks (aged 3-1/2 years and greater) in the population after a simulated 10 years. Results are values recorded in January. Initial population was 35 bucks, 100 does, and 100 fawns born in July with a fawn survival of 70%

Doe survival rates		Buck survival rates		Results after 10 years		
Yearlings	Adults	Yearlings	Adults	Total deer	Total bucks	Trophy bucks
80	85	70	75	777	211	91
70	75	70	75	267	96	53
70	75	60	65	228	57	22

after a simulated 10 years dependent on the buck and doe survival rates (table 5). If doe survival rates drop from 80% to 70% for yearlings and from 85% to 75% for adults and the survival rates for bucks remain at 70% for yearlings and 75% for adults, a variety of changes occur within the deer population. After 10 years the total number of deer (267) will be about unchanged from the original population (235), but about 34% of the number expected (777) had the survival of the does not been modified. At the same time the total buck population (96) will be 45%, and the "trophy" buck (those 3-1/2 years old and older) population (53) will be 58% of that expected (211 and 91, respectively) had survival rates of the population not been reduced (table 5).

Hunters with antlerless deer permits frequently kill an antlerless deer only if they cannot find a buck. This may increase buck mortality since both hunters with permits for antlered deer and those hunters with permits for antlerless deer are trying for the same resource. The combination of reduced survival rates for both bucks and does will cause total buck and trophy buck populations to decrease at greater rates than the deer population itself. If, for example, buck mortality is always about 10% greater than doe mortality, then as doe survival rates drop from 80% to 70% for yearlings and 85% to 75% for older does, buck survival rates will drop from 70% to 60% for yearlings and 75% to 65% for older bucks. Total deer numbers (228) under these conditions become 29% of those expected (777) had survival rates not been changed, and total bucks (57) would be only 27% and trophy bucks (22) only 24% of the unmodified totals (211 and 91, respectively) (table 5). The percentage of trophy bucks in the total deer kill on the north Kaibab seems to have decreased under limited either-sex deer hunting similar to that discussed in this paragraph (fig. 15).

Figure 15.—Trophy bucks (3-1/2 years old and older) as a percent of the total deer kill on the north Kaibab, Arizona (from McCulloch 1975).

The hunting of antlerless deer is a valid management tool for maintaining a deer population within habitat-carrying capacity in deer herds with the high productivity rate of the north Kaibab herd. An increase of as little as 10% in doe mortality may be sufficient to hold the deer population in check. A larger increase in doe mortality rate may reduce the total deer population. A combination of antlerless deer hunting and heavy buck hunting will shorten the age-structure of the buck population and, consequently, reduce the number of trophy bucks on the range.

SUMMARY

It seems very likely that the limited productivity of many southwestern deer populations limits herd growth. Fetuses per doe and fawns per doe are frequently lower in the Southwest than in other deer herds. Deer management theories have often been based on deer populations with the potential to explode under favorable habitat conditions. These herds have high reproductive rates, good fecundity among young age classes, and high survival rates in fawn and yearling crops and considerable hunting pressure is required to keep population levels within habitat-carrying capacities. The situation in much of New Mexico and especially in Arizona seems to be one of only modest reproductive rates, limited fecundity in young age classes, and only fair sur-

vival of young deer. These populations approach habitat-carrying capacity very slowly. Heavy harvest, particularly of antlerless deer, may depress a deer herd for several years, rather than stimulate any increased reproductive response. Many southwestern deer herds apparently act as long-age-structured herds rather than short-age-structured herds and must, consequently, be managed more adroitly than populations with a greater capacity for growth.

Principles about the management of southwestern deer herds may be applicable to many other western herds. A first analysis suggests that many of these other herds have a greater fawn-production rate. If, however, high overwinter mortality of fawns is usual, then there may be greater similarity in the yield of yearling deer in western and southwestern deer herds than production data based on fetal counts would suggest. If this is the case, then the impact of hunting does in western herds would be similar to the impact to southwestern deer herds discussed in this paper. Interestingly, some herds of Rocky Mountain mule deer have apparently declined coincidentally with the introduction of the harvesting of antlerless deer. The dynamics of these western deer herds should be carefully analyzed to see if hunting antlerless deer is an adverse factor in local deer herd management. It is obvious the principles of deer management developed on the basis of some highly productive eastern deer ranges are not wholly applicable to management of the western mule deer.

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Appendix

Table A1.—Plant species eaten by southwestern deer at different seasons. Notation of L, M, or H usage indicates that a plant item composed 1-5%, 6-15% and 16% or more, respectively, of rumen contents. Literature references follow the table

Food items	Winter	Spring	Summer	Autumn	Reference no.[1]
Browse					
Quercus sp.	H	M	H	M	1,2,4,5,8,11,12
Juniperus sp.	H	L	M	M	1,3,6,11,12,13
Cercocarpus sp.	H	M	M	H	1,2,3,4,5,8,11,12
Yucca sp.	H	H	L	L	1,4,12
Rhus sp.	L	L	M	M	1,4,8,12
Garrya sp.	M	L	L	L	1,2,3,4,8,12
Artemisia sp.	L	L	M	M	1,4,6,13
Eriogonum sp.	H	L	L	M	4,5,6,8,10,11,13
Abies concolor	M		M	L	2,9,13
Prosopis sp.	L		M	L	4,5,10
Rhamnus crocea	M	M	L	L	4,5,11
Ceanothus sp.	M	M	L	M	4,5,7,11,12
Calliandra eriophylla	H	M	L	H	4,7,10
Pinus ponderosa	H	L	L	L	5,9,13
Pinus edulis	L			L	1,6
Gutierrezia sp.	L			L	1,6
Acacia sp.	L	H	L	L	4,10
Cowania sp.	M			M	6,13
Populus tremuloides			H	M	9,13
Nolina sp.	L	L			1
Fallugia paradoxa	L	L			1
Juglans sp.			L		1
Mahonia haematocarpa			L		1
Pseudotsuga menziesii				M	3
Simmondsia chinensis			L	M	4
Lonicera interrupta				L	4
Atriplex canescens				L	6
Mimosa dysocarpa			H	M	7
Picea engelmannii			L		9
Robinia neomexicana			L		9
Chilopsis linearis		L			10
Vauquelinia californica		L			10
Fouquieria splendens		L			10
Vitis arizonica				M	12
Krameria sp.		M	M		4,7
Phoradendron sp.	L	L	L	L	3,4,6,12,14
Opuntia sp. (fruit)	L	L	L	L	1,4,10
Carnegiea gigantea (fruit)			L		4
Ferocactus wislizenii	H	M	L	H	10
Agave sp.				L	12
Cholla sp. (fruit)	M			L	14
Forbs					
Baileya multiradiata		L			10
Descurainia pinnata		M			10,14
Lupinus sp.	L		L	L	4,6,7,13
Sphaeralcea sp.		L	L	L	1,4,6
Viguiera sp.			L	M	1,13
Penstemon sp.	L			M	4,6
Erigeron sp.			M	L	6,9
Lotus sp.			L	L	6,9
Agoseris sp.			L	L	7,9
Linum sp.	L			M	1
Euphorbia sp.	M	L	M		1,4

Table A1.—Continued

Food items	Winter	Spring	Summer	Autumn	Reference no.[1]
Dyssodia papposa			M		1
Melampodium leucanthum		L	L	L	1
Coreopsis tinctoria	L				1
Verbena sp.		L	L		1,10
Trifolium sp.			L		1,9
Salsola kali		L			1
Solanum xantii		L	L		4
Porophyllum gracile				L	4
Tradescantia occidentalis				M	4
Erodium cicutarium	L			L	4
Margaranthus solanaceus				L	4
Franseria confertiflora	L				4
Cuscuta sp.		M			4
Comandra pallida		L			4
Cordylanthus tenuifolius	L				5
Hymenopappus lugens				L	6
Delphinium andesicola			M	M	7
Cassia leptadenia			L	L	7
Polygonum aviculare			L		9
Eriastrum sp.		M			10
Apodanthera undulata			L		10
Potentilla sp.			M		13
Astragalus sp.		L	L	L	6,8,9,13
Ipomoea sp.			L	L	4,7,8
Physalis sp.			L		8
Dalea sp.		M	M	L	14
Desmanthus cooleyi		M	M		14
Commelina dianthifolia			M		14
Cucurbita foetidissima		L		L	14
Dichelostemma pulchellum		M			4
Grass and grasslike					
Gramineae	L	L	L	M	1,3,5,8,10,12
Bromus sp.	L		L	L	4,6,9
Agropyron sp.	L		L	L	5,6,9
Poa sp.			L	L	6,9
Sitanion hystrix	L	M			5
Bouteloua sp.			L	L	7
Dactylis glomerata			M		9
Other					
Mushrooms			M		13
Lichens	L			L	1

[1]References:
1. Anderson et al. 1965
2. Day 1961
3. Day and Welch 1959
4. McCulloch 1973
5. Neff 1974
6. McCulloch 1969
7. White 1961
8. Boeker et al. 1972
9. Hungerford 1970
10. Short 1977
11. Illige 1953
12. Day 1963
13. Wright 1950
14. Short et al. 1977

Table A2.—Approximate composition of the diet of southwestern deer in different habitats during different seasons

Deer species	Reference[1]	Habitat type	Season	Source	Shrubs and trees	Forbs	Grass and grasslike	Other	Total
White-tailed	1	Mixed conifer	Autumn	Rumen analysis	47				
	2	Mixed conifer—2287 m	Autumn	Rumen analysis	50 +				
	2	Below 2287 m	Autumn	Rumen analysis	74				
	3	Chaparral-desert	Winter	Rumen analysis	68	27	5		100
	3	Chaparral-desert	Spring	Rumen analysis	85	10	[2]	5	100
	3	Chaparral-desert	Summer	Rumen analysis	84	16	[2]		100
	3	Chaparral-desert	Autumn	Rumen analysis	49	48	3		100
	4	Ponderosa pine	Sum., aut., and win.	Percent feeding time	9	91			100
	4	Oak woodland	Sum., aut., and win.	Percent feeding time	97		3		100
Mule	3	Chaparral-desert	Summer	Rumen analysis	90	6	[2]	4	100
	3	Chaparral-desert	Autumn	Rumen analysis	92	8	[2]		100
	3	Chaparral-desert	Winter	Rumen analysis	75	21	4		100
	3	Chaparral-desert	Spring	Rumen analysis	66	24	[2]	10	100
	5	Unburned pinyon-juniper	Autumn	Rumen analysis	60	33	7		100
	5	Burned pinyon-juniper	Autumn	Rumen analysis	15	52	33		100
	6	Ponderosa pine	Summer	Percent feeding time	47	34	18	1	100
	7	Semi-desert grassland	Spring	Rumen analysis	42	23	3	32	100
	7	Semi-desert grassland	Summer	Rumen analysis	62	22	1	15	100
	7	Semi-desert grassland	Autumn	Rumen analysis	51	3	[2]	46	100
	7	Semi-desert grassland	Winter	Rumen analysis	37	4	1	58	100
	8	Pinyon-juniper	Yearlong	Estimated weight consumed	62	31	7		100
	8	Ponderosa pine	Yearlong	Estimated weight consumed	46	44	10		100
	9	Pinyon-juniper	Yearlong	Rumen analysis	70	26		4	100
	10	Pinyon-juniper	Yearlong	Rumen analysis	75	16	2	7	100
	11	Pinyon-juniper	Winter	Rumen analysis	94	2	1	3	100
	11	Pinyon-juniper	Spring	Rumen analysis	58	32	1	9	100
	11	Pinyon-juniper	Summer	Rumen analysis	51	42	1	6	100
	11	Pinyon-juniper	Autumn	Rumen analysis	87	4	4	5	100

[1]References:
1. Day 1961
2. Day and Welch 1959
3. McCulloch 1973
4. White 1961
5. McCulloch 1969
6. Hungerford 1970
7. Short 1977
8. Neff 1974
9. Anderson et al. 1965
10. Boeker et al. 1972
11. Short et al. 1977

[2]Trace

Table A3.—Productivity of different age classes of does from southwestern ranges

Range	Years	Reference[1]	Age classes	Number of does	Mean value per doe[2]
			months		
Mule Deer					
Guadalupe Mountains New Mexico	1957-58	1	15-17	100	0.01 c.a.
			27-29	105	0.88 c.a.
			39-53	73	1.12 c.a.
			63-99	67	1.55 c.a.
			99 +	56	2.04 c.a.
South Kaibab Arizona	1944-52	2	15		0.09 c.a.
			27		0.64 c.a.
			39-87		2.17 c.a.
			99 +		2.35 c.a.
	1953-54	3	15	20	0.05 c.a.
			27	17	0.88 c.a.
			39-63	25	1.64 c.a.
			75-99	21	2.19 c.a.
			99 +	8	3.13 c.a.
North Kaibab Arizona	1944-52	2	15		0.10 c.a.
			27		0.83 c.a.
			39-87		1.55 c.a.
			99 +		2.22 c.a.
	1953-54	3	15	161	0.0 c.a.
			27	62	0.81 c.a.
			39-63	187	1.46 c.a.
			75-99	133	2.41 c.a.
			99 +	166	2.83 c.a.
Three Bar Area Arizona	1962-66	4	33-96	12	1.25 F
Mingus Mountain Arizona	1954	3	15	8	0.0 c.a.
			27	8	0.88 c.a.
			39-63	8	2.50 c.a.
Moqui, Arizona	1953-54	3	15	15	0.0 c.a.
			27	42	1.05 c.a.
			39-63	48	1.77 c.a.
			75-99	54	2.63 c.a.
			99 +	22	4.14 c.a.
Santa Rita Experiment Range, Arizona	1969-71	5	0-12	5	0
			13-24	2	1.00 F
			25-36	0	0
			37-96	8	1.50 F
			97 +	2	0.50 F
Northern Utah	1954	6	Fawns	5	0.20 F
			15	7	1.38 F
			27	1	2.00 F
			39	1	2.00 F
			48-89	8	2.12 F
			99 +	4	2.25 F
Wasatch Front Utah	1950-53	7	15	128	1.11 F
			27	78	1.76 F
			39-87	234	1.70 F
			99 +	123	1.64 F
White-Tailed Deer					
Chiricahua Mountains Arizona	1955	8		33	0.79 c.a.
	1956	8		29	1.07 c.a.
	1958	8		61	1.11 c.a.
Fort Huachuca Arizona	1956	8		21	1.14 c.a.
	1959	8		17	0.94 c.a.

[1]References
1. Anderson et al. 1970
2. Illige 1953
3. Swank 1956b
4. McMichael 1967
5. This report
6. Jensen and Robinette 1955
7. Robinette et al. 1955
8. Day 1960

[2]c.a. = number corpora albicantia
F = number fetuses per doe

Table A4.—Simulated changes in herd size and structure after 10 years when different segments of the deer population survive at different rates. Original population consisted of 125 fawns, 10 yearling does, 20 2-year-old does and 70 3-year-old and older does. Yearling does are assumed to produce a single fawn at 24 months of age and mature does to produce an average of 1.5 fawns at 3 years of age and at 12 month intervals thereafter. The doe population after 10 years is listed as a percent of the original doe population. Yearling does are listed as a percent of total does in the population. Three right hand columns represent deer numbers and ratios measured in January

Annual survival rates			Fawn:doe ratio	Doe population (Y + A) after 10 years as percent of original Y + A	Yearling does (Y) as percent of Y + A does
Fawns (F)	Yearling does (Y)	Adult does (A)			
80	80	90	81	901	26
		70	76	224	28
		50	70	44	30
	60	90	86	498	22
		70	82	105	24
		50	74	19	26
	40	90	93	242	17
		70	90	40	18
		50	100	2	0
	20	90	104	99	10
		70	100	10	10
		50	0	0	0
70	80	90	73	676	24
		70	68	160	26
		50	64	28	29
	60	90	77	391	20
		70	73	77	22
		50	64	11	27
	40	90	84	196	15
		70	79	29	17
		50	0	0	0
	20	90	92	87	9
		70	100	6	0
		50	0	0	0
60	80	90	65	498	22
		70	61	105	24
		50	60	15	20
	60	90	69	296	18
		70	64	53	21
		50	67	6	17
	40	90	74	159	14
		70	70	20	15
		50	0	0	0
	20	90	80	75	8
		70	75	4	0
		50	0	0	0
50	80	90	56	356	19
		70	54	69	22
		50	44	9	22
	60	90	59	221	16
		70	57	35	17
		50	50	2	0
	40	90	64	121	12
		70	60	15	13
		50	0	0	0
	20	90	68	62	6
		70	75	4	0
		50	0	0	0

Table A4.—Continued

Annual survival rates: Fawns (F)	Annual survival rates: Yearling does (Y)	Annual survival rates: Adult does (A)	Fawn:doe ratio	Doe population (Y+A) after 10 years as percent of original Y+A	Yearling does (Y) as percent of Y+A does
40	80	90	47	238	17
		70	45	40	18
		50	50	2	0
	60	90	49	160	14
		70	45	22	14
		50	0	0	0
	40	90	52	99	10
		70	44	9	11
		50	0	0	0
	20	90	55	51	4
		70	50	2	0
		50	0	0	0
30	80	90	37	160	14
		70	32	19	16
		50	0	0	0
	60	90	38	102	11
		70	33	12	8
		50	0	0	0
	40	90	40	75	8
		70	25	4	0
		50	0	0	0
	20	90	42	43	2
		70	0	2	0
		50	0	0	0
20	80	90	26	97	9
		70	22	9	11
		50	0	0	0
	60	90	26	74	8
		70	25	4	0
		50	0	0	0
	40	90	27	51	4
		70	0	2	0
		50	0	0	0
	20	90	28	36	3
		70	0	1	0
		50	0	0	0

Short, Henry L. 1979. Deer in Arizona and New Mexico: Their ecology and a theory explaining recent population decreases. USDA For. Serv. Gen. Tech. Rep. RM-70, 25 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

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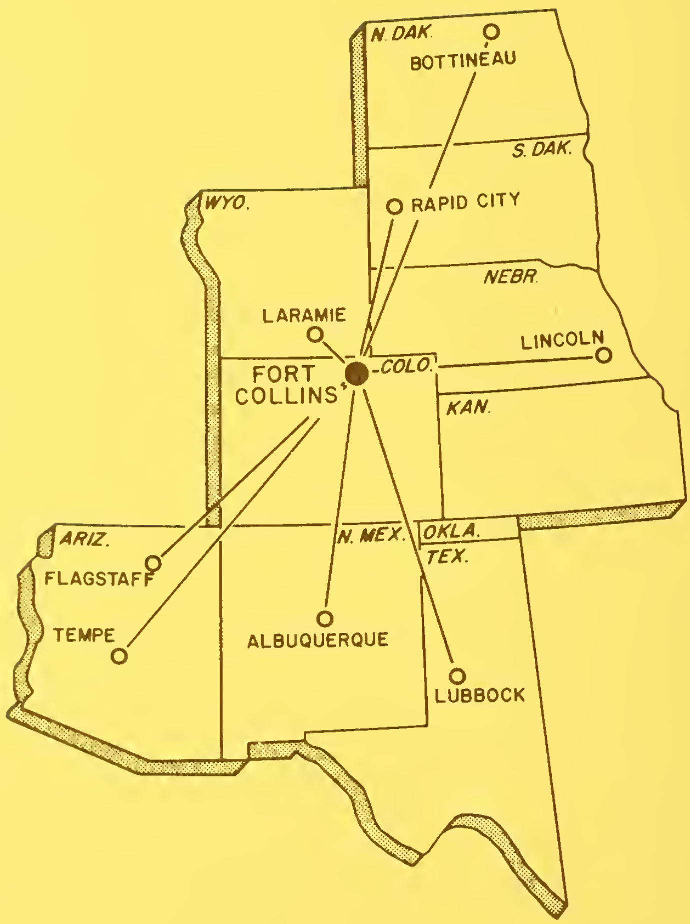
The hypothesis that declines in southwestern deer populations from late 1950's levels have been caused by relatively low fawn recruitment rates (because of habitat quality) combined with increased female mortality (because of antlerless deer hunting) is supported by computer simulations of the dynamics of southwestern deer herds.

Keywords: Wildlife management, *Odocoilius hemionus*, *O. virginianus*, wildlife ecology, population dynamics.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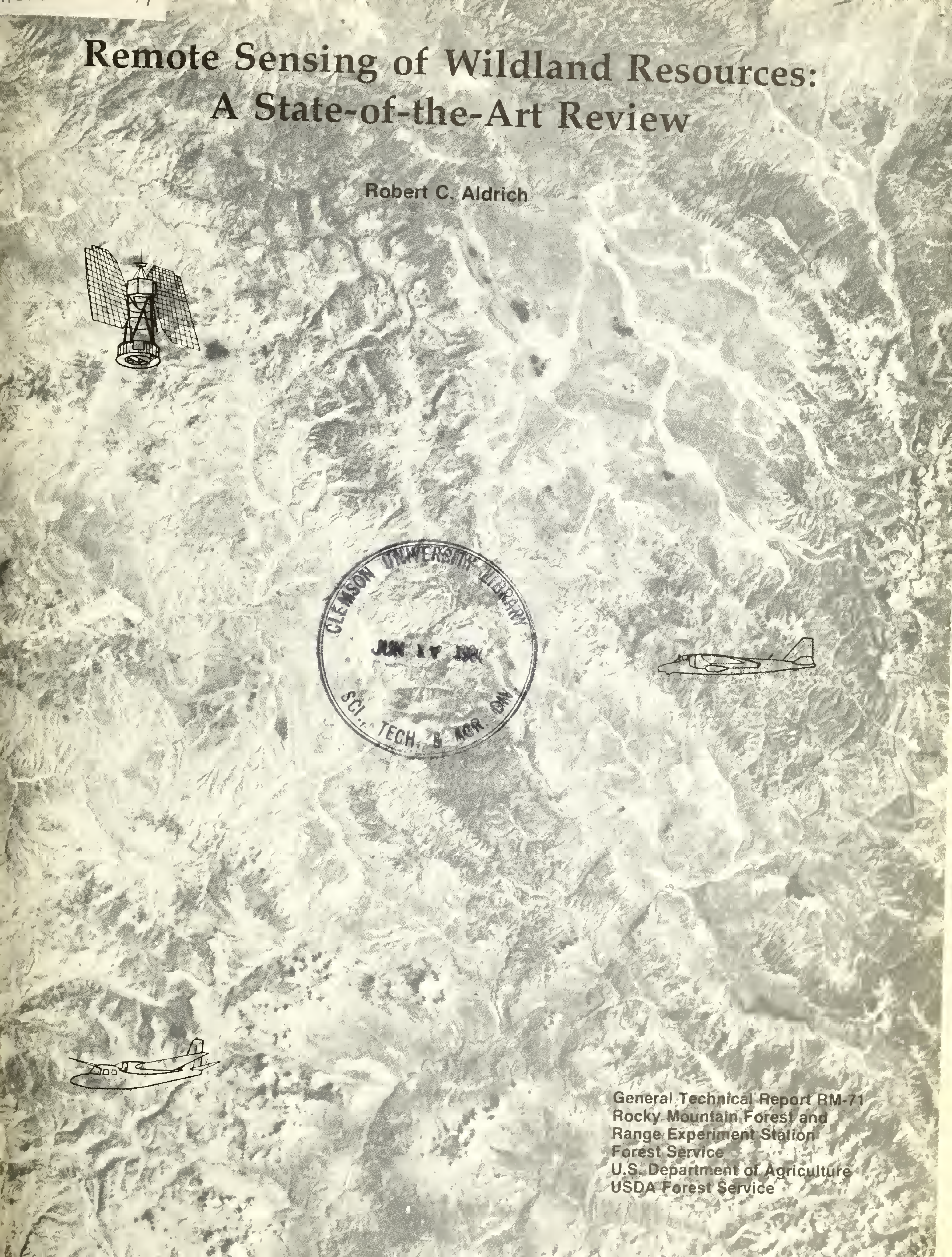
Remote Sensing of Wildland Resources: A State-of-the-Art Review

Robert C. Aldrich



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General Technical Report RM-71
Rocky Mountain Forest and
Range Experiment Station
Forest Service
U.S. Department of Agriculture
USDA Forest Service

Abstract

A review, with literature citations, of current remote sensing technology, applications, and costs for wildland resource management, including collection, interpretation, and processing of data gathered through photographic and nonphotographic techniques for classification and mapping, interpretive information for specific applications, measurement of resource parameters, and observations and counts of occurrences.

General Technical Report RM-71

December 1979

Remote Sensing of Wildland Resources: A State-of-the-Art Review

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Contents

Remote Sensing of Wildland Resources: A State-of-the-Art Review[2]

Robert C. Aldrich

INTRODUCTION

Remote sensing is a tool to aid gathering information about land cover with a minimum of ground verification. How much information is extracted from remotely sensed data is dependent upon the type of sensor and the portion of the electromagnetic spectrum (EMS) used, the quality of the data recorded, and certain physical limitations including platform altitude, topography, variations in solar angle and solar altitude, and atmospheric interference. There are other limiting factors involved in processing the data once they have been collected (i.e., regardless of how well data are gathered, improperly processed and/or interpreted data will yield poor information, preventing realization of the full capabilities of remote sensing).

The "state" of something is the sum of the qualities involved in its existence at a particular time and place. The qualities of remote sensing as defined here include the data as well as the data collection, interpretation, and/or data processing. The end result must be cost-effective information useful to resource managers for land use planning and solving wildland management problems. Remote sensing as reviewed in this paper covers both photographic and nonphotographic data including microwave, radar, thermal infrared (thermal IR), ultraviolet (UV), as well as multispectral scanner (MSS) data. Nonimaging radiometers and spectrometers, however, are not included. Remotely sensed data may be interpreted manually (photo interpretation), by automatic data processing (ADP), or by a combination of the two.

TERMINOLOGY

It would be difficult to discuss the state of remote sensing without reference to several basic technical terms. These terms are defined here to avoid confusion and the need for repetition later in the review. A more complete glossary of remote sensing is found in appendix A.

Ground resolution.—For this review, ground resolution refers to the smallest detectable or measureable detail on a remotely sensed image. In aerial photography, ground resolution is a function of scale (camera lens focal length and flying height above ground) and the resolving power of a system. To measure an object or condition on photographic films requires a finer ground resolution than to detect it. This is because of granularity in the processed image and because of light scattering during exposure. Thus, resolution is the ability of an entire remote sensing system, including lens, antennae display, exposure, processing, and other factors, to render a sharply defined image.

The required ground resolution for each application in this review was taken from a U.S. Department of Agriculture (USDA) Forest Service Data Users Requirements Task Force Catalog (see INFORMATION NEEDS—THE USER REQUIREMENTS). Ground resolutions obtainable by each film were based upon system resolving power (including camera lens, film, and image motion during exposure) and were interpreted from Welch (1972) (table 1). The use of trade and company names is for the benefit of the reader; such use does not constitute an official endorsement or approval of any service or product by the USDA to the exclusion of others that may be suitable.

Resolving power.—Resolving power refers to changes in resolution in an image that depend on film, relative lens aperture, lens aberations, and the angular distance of the object from the optical axis. It is usually expressed in number of line pairs (black and white bar targets) visible per millimeter of film. As the field angle (field of view or aperture) of a lens increases, the resolving power decreases. Sometimes a lens is the limiting factor in resolving power of a system if its resolving power is less than the resolving power of other system components. The same logic can be applied to other components of the system; the resolving power of a system can be no better than its weakest component.

[2]*The author wishes to thank Professor Robert C. Heller, University of Idaho; Professor Roger M. Hoffer, Purdue University; Wayne G. Rohde, Technicolor Graphic Services, Inc. (EROS Data Center); and Ray P. Allison, Remote Sensing Coordinator, USDA Forest Service, for their helpful reviews of this paper. Their comments and suggestions lead to many improvements in the manner of presentation as well as content.*

Table 1.—Photographic film and scale requirements to detect and measure USDA Forest Service ground target resolutions[1]

Ground resolution requirement	Photographic requirement by			
	Detection		Measurement	
	IR and CIR[2]	BW and color[2]	IR and CIR[2]	BW and color[2]
m	Photographic scale			
	Aircraft platforms[3]			
0.1	1:3,200	1:5,000	1:1,600	1:2,500
0.3	1:12,500	1:20,000	1:6,400	1:9,600
0.5	1:20,000	1:32,000	1:9,600	1:16,000
1.0	1:40,000	1:64,000	1:20,000	1:32,000
1.5	1:64,000	—[5]	1:32,000	1:46,000
2.0	—[5]	—	1:40,000	1:64,000
3.0	—	—	1:64,000	—[5]
	High altitude and space platforms[4]			
1.0	1:64,000	1:125,000	1:32,000	1:64,000
1.5	1:92,000	1:184,000	1:46,000	1:92,000
2.0	1:125,000	1:250,000	1:64,000	1:125,000
3.0	1:184,000	1:320,000	1:92,000	1:160,000
4.0	1:250,000	1:500,000	1:125,000	1:250,000
5.0	1:310,000	1:620,000	1:155,000	1:310,000
10.0	1:500,000	1:1,000,000	1:250,000	1:500,000
30.0	1:1,500,000	1:3,000,000	1:750,000	1:1,500,000
80.0	1:3,900,000	1:6,000,000	1:2,100,000	1:2,600,000

[1]Tabular values were read from graphs adapted from figure 9 of Welch (1972) and rounded for consistency.

[2]BW–panchromatic, IR–infrared, color–normal color, CIR–color infrared (Aerochrome Infrared)

[3]150- to 9,200-m altitude; films referred to are Eastman Kodak Infrared Aerographic 2424 (IR), Aerochrome Infrared 2443 (CIR), Panatomic 3410 (BW), Aerocolor 2445 (color), and Aerochrome MS 2448 color.

[4]9,200-19,800 m and above 190 km altitude; films referred to are Eastman Kodak High Definition Aerochrome Infrared SO-127 (CIR), High Definition Aerial 3414 (BW), and Aerial Color, SO-242 (color).

[5]Theoretically, scales smaller than 1:64,000 cannot be obtained from a 9,200-m altitude unless a lens focal length shorter than 6 inches (150 mm) is used. There is no precedence for doing this. Since lower resolution requirements can be achieved at 1:64,000, the chart is not extended beyond this point.

Contrast.—Contrast is the distinction between two objects on remotely sensed images and is dependent upon the ratio of the energy reflected by those two objects, the sensor sensitivity, solar illuminance, atmospheric luminance, and atmospheric transmittance (American Society of Photogrammetry 1975). The resolving power of aerial films is usually given in terms of contrast ratios of 1,000:1 or 1.6:1, high contrast targets and low contrast targets, respectively. In reality most natural objects have ratios of less than 5:1 and contrast ratios closer to 2:1when other factors cited are taken into account.

Scale.—Scale refers to a representative fraction, or the ratio of a unit of measured distance on the image (usually 1 inch) to the measured distance represented on the ground expressed in the same units of measure. The smaller the fraction (i.e., the larger the divisor of the fraction) the smaller the scale. Small scales in this review lie between 1:30,000 and 1:200,000, medium scales lie between 1:12,000 and 1:30,000, and large scales are from 1:500 to 1:12,000. Imagery smaller than 1:200,000 (including satellite imagery) is considered very small-scale imagery and requires special viewing equipment with enlarging stereo or monoscopic optical systems (table 2).

The finest detail recorded on photographic film today can only be observed by magnification. In effect, magnification corresponds to a change in scale (Welch 1972). For obvious reasons, then, any reference to a terrain feature observed on a photograph of a certain scale means very little from a systems evaluation point of view. The image-forming properties of the film, the camera system, and the additional magnification must also be referred to (table 2).

Electromagnetic spectrum.—The EMS is an ordered array of known electromagnetic radiations (energy) (American Society of Photogrammetry 1975). In this review only those portions of the EMS known to be useful for gathering wildland informa-

tion are considered (fig. 1). These portions include UV (0.28-0.4 μm), visible (0.4-0.7 μm), photo IR (0.7-0.9 μm), near IR (0.9-1.3 μm and 1.3-3.0 μm), middle IR (3.0-13.8 μm), and the microwave wavelengths of radio energy (0.1-77.0 cm). The microwave portion of the EMS is further divided into passive (0.1-3.0 cm) and active microwave (radar, 0.5-77.0 cm).

Band.—In this paper "band" refers to a selection of wavelengths in the EMS (e.g., from 0.6 to 0.7 μm is defined as the red band of the visible spectrum) or it can be a range of radar frequencies referred to as the X-, K- or L-band.

Instantaneous field of view.—Instantaneous field of view (IFOV) denotes the narrow field of view designed into scanning radiometer systems (thermal scanners and MSS's), so that, while about 120° may be under scan at any one instant, only electromagnetic energy from the small area covered by the field of view is being recorded (American

Table 2.—Magnification and instrumentation necessary to interpret and/or classify and map from photographic remote sensing imagery

Photographic scale[1]		Required magnification[2]	Data type[3]	Recommended instrument or method[4]
Representative fraction	Code			
		–Number of enlargements–		
		Stereoscopic		
1:1,600	01	1.5	P	PS
1:2,500	02	1.5	P	PS
1:3,200	03	1.5	P	PS
1:5,000	04	1.5	P	PS,MS,SS
1:6,400	05	1.5	P	PS,MS,SS
1:9,600	06	1.5	P	PS,MS,SS
1:12,000	07	1.5	P	PS,MS,SS
1:16,000	08	1.5	P	PS,MS,SS
1:20,000	09	1.5	P	PS,MS,SS
1:32,000	10	2.0	P	MS,SS
1:40,000	11	3.0	P	MS,SS,ZS
1:46,000	12	3.0	P	MS,SS,ZS
1:64,000	13	3.5	P	MS,SS,ZTS,ZS
1:83,000	14	4.0	P	ZTS,MS,SS,ZS
1:92,000	15	4.5	P	ZTS,MS,SS,ZS
1:100,000	16	5.0	P	ZTS,SS,ZS
1:125,000	17	6.0	P	ZTS,SS,ZS
1:150,000	18	6.5	P	ZTS,SS,ZS
1:155,000	19	6.5	P	ZTS,SS,ZS
1:160,000	20	7.0	P	ZTS,SS,ZS
1:184,000	21	8.5	P	SS,ZS
1:200,000	22	9.0	P	SS,ZS
		Monoscopic		
1:250,000	23	11.0	P,D	SM,PE(ZTS),DIAS
1:310,000	24	13.0	P,D	SM,PE(ZTS),DIAS
1:320,000	25	14.0	P,D	SM,PE(ZTS),DIAS
1:375,000	26	15.0	P,D	SM,PE(ZTS),DIAS
1:500,000	27	20.0	P,D	SM,PE(ZTS),DIAS
1:620,000	28	23.0	P,D	SM,PE(ZTS),DIAS
1:750,000	29	26.0	P,D	SM,PE(ZTS),DIAS
1:1,000,000	30	35.0	P,D	SM,PE(ZTS),DIAS
1:1,250,000	31	39.0	D,P	DIAS,PE(ZTS)
1:1,500,000	32	45.0	D,P	DIAS,PE(ZTS)
1:2,100,000	33	50.0	D,P	DIAS,PE(ZTS)
1:2,600,000	34	55.0	D,P	DIAS,PE(ZTS)
1:3,000,000	35	60.0	D,P	DIAS,PE(ZTS)
1:3,900,000	36	70.0	D,P	DIAS,PE(ZTS)

[1]*Usually 70-mm format*
[2]*Taken from figure 17 of Welch (1972).*
[3]*P–photographs*
D–digitized photographic transparencies.
[4]*PS–pocket stereoscope.*
MS–mirror stereoscope (2X).
SS–scanning stereoscope (2X, 4X, 9X).
ZS–zoom stereoscope (2.5-60X).
SM–stereo microscope (2.5-60X).
ZTS–zoom transfer scope (1-13X).
DIAS–digital image analysis system.
PE–photo enlargement.

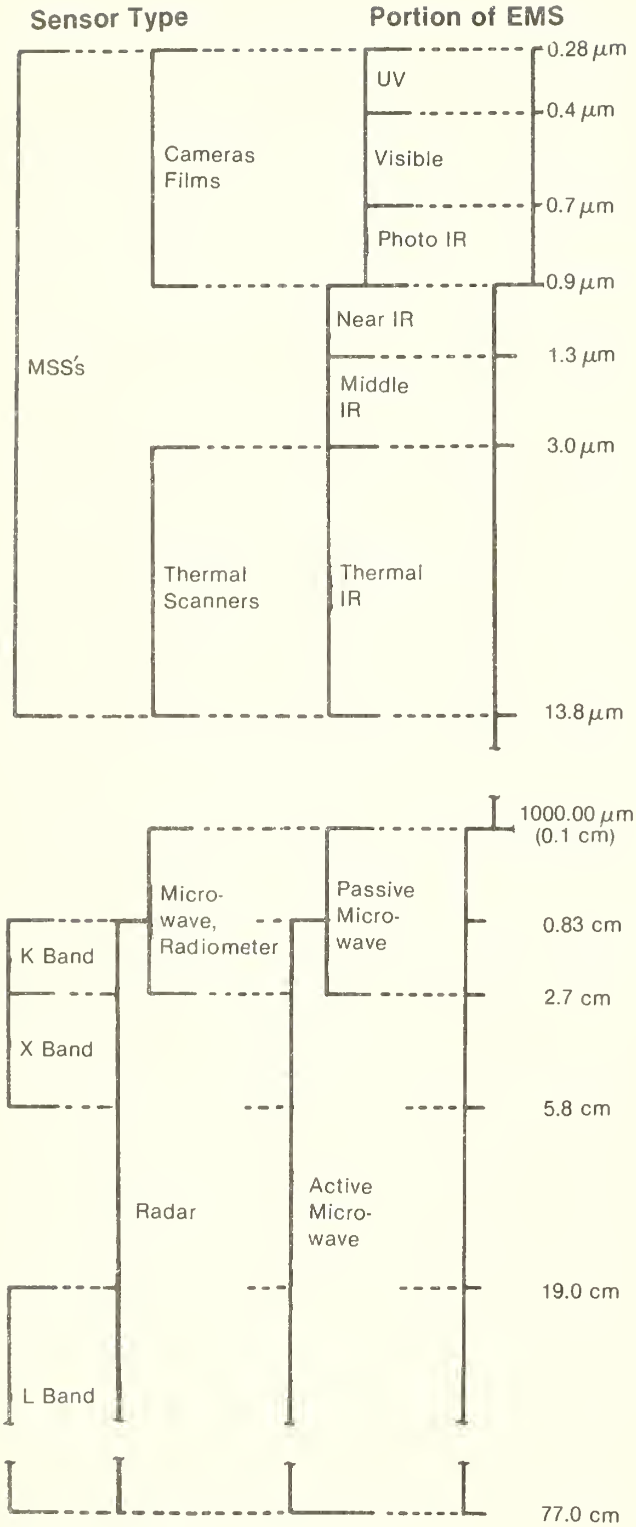

Figure 1.—Useful portions of the electromagnetic spectrum (EMS) and the most effective sensor type. Portions of the EMS are not drawn to scale.

Society of Photogrammetry 1975). For example, the four-band MSS's on Landsat-2 and Landsat-3 subtend an IFOV of 79 m on a side from 920 km above the earth. A cross track IFOV of 57 m is obtained by resampling the signals across the swath at the scanner's electronics output.

Imaging sensors.—In the broadest sense used here, imaging sensors include cameras and films and optical-mechanical scanners—including both thermal scanners and MSS's. These sensors, as well as photographic sensors, are optical devices and are passive sensing systems. Although radar and passive microwave systems are considered imaging systems, they are not optical devices.

BACKGROUND

A review of the state of remote sensing is a formidable task when one considers the abundance of literature printed on the subject during the past 10 years. This abundance has been caused largely by the Earth Resources Survey Program of the National Aeronautics and Space Administration (NASA). Through this program NASA has made outstanding contributions to the development of remote sensing technology. It is unfortunate, however, that not all of what is written is worthy. Much of the "oversell" of remote sensing in recent years has come from overly enthusiastic individuals and their agencies. Many times speculative statements at the end of inconclusive studies have been quoted out of context (Buys 1973) and blown out of proportion, resulting in a credibility gap between the remote sensing community and the user community (Murtha 1976).

Space and time do not permit a thorough review of every paper published on wildland resources during the past 10 years. However, a careful review of indexes to scientific journals, publications of abstracts, and technical information digests revealed pertinent sources of information which were reviewed in greater detail. Source materials included *Photogrammetric Engineering and Remote Sensing, Remote Sensing of Environment, Forest Science, Journal of Forestry, Journal of Range Management, Applied Ecology Abstracts, Forestry Abstracts, Selected Water Resource Abstracts, Wildlife Review, Forestry Chronicle, National Technical Information Service Index, LANDSAT Newsletter, NASA/SCAN Notification, Manual of Remote Sensing,* proceedings of symposia, and research papers and reports. Not every wildland resource subject is addressed in the literature; however, information reported can be interpreted for subjects that are neglected. Publications on many subjects were inconclusive, and many times conclusions overstated the results of experiments.

INFORMATION NEEDS—THE USER REQUIREMENTS

To manage wildlands, information is needed to address all USDA Forest Service resource systems (forest and rangeland, outdoor recreation and wilderness, wildlife and fish, range, timber, and water). To make an assessment of the potential effects of alternative land uses on resource systems requires basic information on soils, vegetative cover, water, landform (topography), and climate and their relationship to each other. An inventory of current and potential productivity of land is also needed by resource managers making land use and management decisions. Some local management and planning decisions require mapped or pinpointed information. Other decisions at the state, regional, and national levels may be based upon statistical data derived from extensive samples. Regardless, the basic information required to satisfy program plans (national, state, or regional), environmental impact statements, management plans, and day-to-day management operations differs only in resolution. For example, national planners may need to know timber volume by broad softwood or hardwood categories by regions, regional planners may need timber volume by states by broad forest types, and state planners may need timber volume by counties by specific forest types. The parameter to be measured, accuracy required, and the way the data are formatted will differ accordingly.

In 1978 a USDA Remote Sensing User Requirements Task Force (required by the Secretary's Memorandum No. 1822 dated August 17, 1973) identified over 800 USDA Forest Service information requirements. These requirements were compiled in a computer printout called the Data Users Requirements Task Force Catalog. Each requirement was addressed in terms of its current potential or its future potential for being classified, interpreted, or measured by remote sensing.

The USDA Forest Service's information requirements attainable now or by further remote sensing research and development were examined and recommendations were made for either aerial or satellite platforms, the required ground resolution, and the best remote sensor type. Platforms (vehicle type and altitude) in this present review are considered a consequence of the sensor type and the ground resolution required and not an independent, and thus limiting factor for sensor selection.

A review of the remote sensing user requirements revealed that most requirements can be divided into four major groups based upon application.

Classification and mapping application.—These applications require some observational and interpretive skills to delineate homogeneous areas of cover. Delineations might be made by drawing a boundary line or by point sampling with listings of points by cover type. Units of land are classified by vegetative cover, nonvegetative cover, land use, land form, or disturbance.

Interpretive information for specific applications.—These applications may require some observational and measurement skills to answer a management problem within a designated area or at a certain location. Information interpreted from remotely sensed data in this sense does not result in a map. It could confirm that a certain condition exists, locate and flag the condition, and provide certain corollary information needed to manage condition. Some examples might be the location of an unusual stress condition, potential landslide, geological hazards, soil erosion, oil slicks, and other water pollutants.

Measurements of resource parameters.—These measurements include linear distances, heights, numbers, area, and other expressions of the size, quantity, or quality of basic resources.

Observation and counts of occurrences.—This category is defined as the determination of the presence or absence of something—a building, structure, cars, people, animals, road washouts, erosion, and others.

Two hundred eleven nonoverlapping user requirements (app. B) were extracted from the User Requirements Catalog and assigned to 1 of these 4 major and 45 secondary application areas (table 3). The assignment of a particular requirement to one application area rather than another was based on the author's experienced judgment. The requirements were organized in this way to reduce the number of application problems to a reasonable number for this review.

REMOTE SENSING SYSTEMS

Before discussing the state of remote sensing for wildland resources, it would be appropriate to review current photographic and nonphotographic data acquisition systems.

PHOTOGRAPHIC SENSING SYSTEMS

Cameras and films were used to collect wildland resource information long before remote sensing

Table 3.—Distribution of remote sensing application problems by category[1]

	Application	Number of items
I.	Classification and mapping	87
A.	Vegetative cover	24
B.	Nonvegetative cover	18
C.	Land use	1
D.	Land forms	17
E.	Disturbance	27
II.	Interpretive	36
A.	Land use	3
B.	Wildlife habitat	6
C.	Land use (vegetation)	1
D.	Fire utilization corridor	1
E.	Fuel type	1
F.	Grazeable woodland	1
G.	Vegetative condition	5
H.	Unstable conditions	1
I.	Rock slide barriers	1
J.	Avalanche path	1
K.	Geology	4
L.	Soil type	2
M.	Minerals and construction materials	2
N.	Phenology	3
O.	Tree point occupied	1
P.	Sensecent or dystrophic lakes	1
Q.	Hydrologic condition	1
R.	Natural open areas	1
III.	Measurements	60
A.	Tree and stand	22
B.	Grasses	2
C.	Forbs	1
D.	Brush and shrubs	4
E.	Water	7
F.	Snow	1
G.	Rock slides	2
H.	Gully erosion	3
I.	Sheet erosion	1
J.	Biomass	9
K.	Land use	2
L.	Disturbed area	1
M.	Area of mortality	1
N.	Animal counts	1
O.	Fuel	1
P.	Fire area burned	1
Q.	Dimension of structures	1
IV.	Observations and counts	28
A.	Building and structure	4
B.	Water structures	1
C.	Transportation	3
D.	Recreation	9
E.	Wildlife	2
	Total	211

[1]*Summarized from the U.S. Department of Agriculture, Remote Sensing User Requirements Task Force, Catalog of Requirements, 1978.*

became the popular term for gathering information about objects without physical contact. Some people, however, never speak of photography in the same breath with remote sensing. One explanation for this might be that remote sensing as a technology seemed to evolve with the development of optical-mechanical scanners, other sophisticated sensors, and computer analysis of digital data. This evolutionary association remains to this day. Many of the most renowned centers of remote sensing do little if any research and development in photographic data acquisition and interpretation, although aerial photo data supply most of the ground truth for verification of other remote sensing study results.

Photographic sensors include both camera optics and films. Although cameras are not specified by name or by manufacturer in this review, all references to cameras include the best available mapping cameras and reconnaissance cameras, as well as advanced camera systems for high-altitude and satellite applications. Mapping camera optics are generally capable of resolving 30-40 line pairs per mm (at 1.6:1 contrast). Some high-altitude reconnaissance cameras can resolve over 100 line pairs per mm (American Society of Photogrammetry 1975). It is usually the film, not the camera optics, that restrict ground resolutions obtained by photographic systems.

Films available for aerial photography include panchromatic (BW), IR, color, and color infrared (CIR). The spectral sensitivity of BW and color films are very similar as are sensitivities of IR and CIR films. BW and color films are generally sensitive to the visible portion of the EMS from 0.4 μm (blue) to 0.7 μm (red). IR and CIR films are both sensitive to the visible portion of the EMS but the sensitivity is extended to about 0.9 μm to include some reflected IR. In use, IR and CIR films are usually filtered with a minus-blue (W-12) filter to cut out the blue and blue-green wavelengths and improve haze penetration. Other filters that cut out the blue and blue-green portions of the EMS have been used successfully to accentuate the orange-red portion of the EMS on CIR film. On IR film used with either a Wratten 25A (red) or 89B (dark red) filter, broad-leaved vegetation appears lighter in tone, whereas water and moist soil appear darker in tone. The theory of imaging with photographic sensors has been well documented by Heller (1970).

Film speeds, resolving power, and granularity are reported in Eastman Kodak Publication M-57 (1977). Generally, as film speed increases resolving power decreases. All references to film resolving power or resolution in this review paper are for low contrast subjects (1.6:1) typical of wildland resources.

NONPHOTOGRAPHIC SENSING SYSTEMS

Nonphotographic sensors operate in portions of the EMS from UV through the microwave regions. They include optical-mechanical scanners for multispectral sensing, thermal IR, and active and passive microwave systems.

Multispectral Scanner Systems

MSS's observe the scene under the aircraft or satellite platform in a number of discrete bands of the EMS. Multiple detectors capture and measure reflected energy that can include ultraviolet (0.28-0.4 μm), visible (0.4-0.7 μm), near (0.7-1.3 μm), medium (1.3-3.0 μm), and thermal (3.0-13.8 μm) IR portions of the EMS. This is usually accomplished by allowing the entrance slit of a spectrometer to act as the scanner aperture. Each detector in an array observes the same resolution element of the scene below but in a different wavelength region. Output signals from the detector array can be combined to determine the spectral distribution of the radiation from each resolution element of a scene. Collecting data in this manner provides multispectral data that are registered, easily recorded onto photographic film, and directly compatible with computer processing systems. Commercial systems are available that record data in narrow wavelength bands over the range from UV to far IR.

The dominant factor in determining spectral and spatial resolution of MSS systems is the entrance slit of the spectrometer. The resolution IFOV's for commercially available airborne scanners range from 1 to 3 mrad, or in terms of ground resolution, 1 and 3 m, respectively, for each 1,000 m of altitude above ground. The operational MSS's on Landsat-2 and Landsat-3 have resolution IFOV's of 0.086 mrad (American Society of Photogrammetry 1975), that is, at 920 km above the earth, the ground resolution would be approximately 80 m.

Calibration is an area of primary importance in using MSS's. These calibrations are described in detail in American Society of Photogrammetry (1975), and elsewhere. It is sufficient here to acknowledge that such calibration procedures are important and do exist to measure the ability of an instrument to consistently reproduce the spectral and spatial distribution of radiation from various size elements in the scene. Other necessary corrections include those for lateral distortion (beam velocity while scanning the Earth is nonlinear), motion of the aircraft, and electronically generated image distortions. Acquiring dependable data from optical-mechanical scanners is a complex task.

Thermal Scanner Systems

A thermal scanner consists of a rotating prism mirror and a telescope to focus radiation from a small portion of the Earth's surface. The rotating prism mirror causes the field of view to move smoothly across the object plane (Holter 1970). Each face on the mirror is inclined 45° to the axis of rotation, and as the prism mirror rotates it reflects IR photons through the telescope to a detector. The heart of the scanner is the detector, which transduces (transforms) the incident IR radiation into an electric signal. These signals are most commonly used to record images on a cathode ray tube (CRT) in synchronism with the IR scanner. The face of the tube can be photographed as a permanent record. Signals are also recorded on magnetic tape to display later on a CRT and pictorial record.

Commercially available scanners have IFOV resolutions of 1.5-3.0 mrad (American Society of Photogrammetry 1975) and focal lengths of 2.5-30.0 cm. The IFOV resolutions translate to ground resolutions of 1.5 and 3.0 m, respectively, for every 1,000 m of platform altitude above ground. For example, the thermal band on Landsat-3 has a resolution IFOV of 0.26 mrad which translates to a ground resolution of 240 m at 920 km above ground.[3] The Heat Capacity Mapping Mission (HCMM) satellite launched in May 1978 has a single-channel thermal sensor on board recording over a 1,120-km swath width with a 500-m ground resolution.

Daytime operations for thermal scanners are confined to atmospheric windows of 4.5-5.5 μm and 8.5-13.5 μm with exception of forest fires and volcanic activity (American Society of Photogrammetry 1975). Thermal scanners operate equally well at night and in the period when most forest fire data are collected. Thermal scanners vary by method of data recording and optional ancillary equipment in addition to their performance parameters—resolution, sensitivity, and velocity/height ratio (v/h).

Microwave Sensor Systems

Microwave sensors, including both active and passive systems, are thoroughly described for the nontechnician in American Society of Photogrammetry (1975) and Holter (1970). Active microwave systems (radar) are those that provide their own illumination of the target. In other words, a known signal is transmitted to reflect off the target and back to a receiver. The portion of the signal that is reflected back to the receiver is a function of the

[3] *The thermal band sensor on Landsat-3 failed on July 11, 1978, and was turned off. Diagnostic tests are being performed to determine the cause of failure. Landsat Newsletter 20, April 1, 1978.*

transmitted power, the antennae size, the wavelength of the transmitted energy, the scattering properties of the ground target, the angle of incidence, the signal width, and the distance to the target. The back scattered energy is converted into a spot of light which is regulated according to the strength of the received signal to produce a BW line scan image. A strong return signal is indicated by bright tones whereas a weak return signal is indicated by dark tones.

Passive microwave sensors are not as well developed as sensors in other portions of the EMS. A microwave radiometer is a passive system, meaning signals received by the radiometer are emitted by the target itself. Unfortunately, the self-emitted radio signal is much less than you would find in the IR portion of the EMS. As a result, receivers must be extremely sensitive and have little internal noise. An imaging microwave radiometer is much like the receiver of a radar system. The utility of passive sensors for wildland resources has not been fully explored and very little is known upon which to draw conclusions.

Ground resolution of both active and passive microwave systems is normally poorer than the resolution of sensors in the visible and IR regions. This is because resolution is directly proportional to wavelength, and the shortest microwavelength used is a factor of 100 larger than the wavelength for thermal IR scanning. A fine-angular-resolution for active microwave sensors requires a very large aperture. Generally speaking, resolution capabilities of commercially available imaging radar systems average about 15 m (3-30 m). Most of these systems are confined to the X-band (2.7-5.8 cm). SeaSat, which was launched in June 1978 and became inoperable in November 1978, operated in the L-band (19.0-77.0 cm) and observed ocean dynamics by night and day with a ground resolution of 25 m from an altitude of 800 km.

Some general characteristics of active microwave systems are (1) their ground resolution is generally poorer than that of optical systems; (2) they can sense through cloud cover and some rain; (3) their responses are functions of frequency (or wavelength), polarization, and look angle (as are responses in other portions of the EMS); (4) signal polarization is often used as a discriminant; (5) observational angles well away from vertical are best because of the geometry of radar range measurements; and (6) they can collect data day or night (American Society of Photogrammetry 1975).

Return-Beam Vidicon Systems

The three-sensor return-beam vidicon (RBV) cameras on board Landsat-1 and Landsat-2 are probably the most familiar RBV systems in use today. However, only a limited number of frames of RBV data were ever recorded on Landsat-1 and Landsat-2. Landsat-1 ceased to function on January 6, 1978. These systems represented the state of the art until Landsat-3 was launched on March 5, 1978. RBV cameras are essentially high resolution (5,000 lines per picture) television cameras.

Cameras on board Landsat-1 and Landsat-2 operate in three spectral bands (0.475-0.575 μm, 0.580-0.680 μm, and 0.690-0.830 μm), cover an area on the ground of 185 by 185 km, and have a nominal ground resolution of approximately 44 m for high-contrast objects and 95 m for low-contrast subjects (National Aeronautics and Space Administration 1976a). Landsat-3 cameras are different (National Aeronautics and Space Administration 1976b). They are two identical RBV cameras operating in the broad spectral band from 0.5 to 0.75 μm. These BW-sensitive cameras have a ground resolution of approximately 22 and 42 m for high contrast and low contrast subjects, respectively. This was made possible by doubling the camera focal lengths. The camera IFOV's are aligned side-by-side to view side-by-side nominal 99-km^2 ground scenes with 15-km side laps yielding a 183- by 99-km scene. Two successive pairs of RBV images will nominally cover the same area as one MSS frame. Video signals from the cameras are recorded on magnetic tape at ground stations, where processed tapes and hard copy reproductions are produced with annotations for time and location of the imagery. Although Landsat RBV data, available since 1972, have not been fully evaluated for wildland resource information, the increased spatial resolution of Landsat-3 RBV data shows great promise for mapping and updating maps.

THE STATE OF REMOTE SENSING APPLICATIONS—PHOTOGRAPHIC DATA

Photographic data have been used in wildland resource management activities for over 40 years. Timber inventories, range inventories, and wildlife habitat mapping were purposes for which conventional medium-scaled BW aerial photographs were regularly used (Dolke 1937; Garver 1948; Harris 1951; and Aldrich 1953, 1968). Interpretation used to be based upon photographic tone, texture, shape, size, patterns, shadows, topographic position, and associations. Conventional photointerpretation today is based upon these same variables but with many more options. In 1978 the photointerpreter's job was easier, more satisfying, and done with greater confidence because many color combinations of hue, chroma, and value as

well as IR sensitivity are available. Healthy human eyes can discriminate 1,000 times as many tints and shades of color as they can tints and shades of gray (Ray and Fischer 1957). In addition, improvements in the spectral quality, resolving power and speed of camera lenses and films (BW, IR, color, and CIR), and the use of band pass filters have made it possible to fly aerial photography from both low altitudes (150-3,659 m) and high altitudes (9,200-19,800 m). The information content is equal to or better than the medium-scale BW photography (3,659-9,200 m) of years gone by. Photographs from space, although available only for limited geographic areas following NASA's Gemini, Apollo, and Skylab space programs (1964-1974), have shown that medium resolution imagery can be beneficial in boundary delineations (Colwell 1968, Draeger 1968). In addition, space photographs have other advantages that may prove to be useful for digitizing photographic images to use in interactive ADP systems.

CLASSIFICATION AND MAPPING

Vegetative cover classification is the most important user requirement and the most often used parameter in recent studies of remotely sensed data. But disturbance and nonvegetated cover classification and mapping are also important user requirements. The level in a land cover classification hierarchy, and/or the degree of mapping detail and accuracy needed, dictates the best film and scale for a particular job. Eighty percent or more of the references to applications of remote sensing in wildland managment activities are included in this category.

Conventional Interpretation

Medium-scale aerial photography will continue to be the primary source of USDA Forest Service remotely sensed information. Large-scale aerial photographs will become more economically feasible in the future as the cost of field work increases. The future of small-scale aerial photographs and space imagery rests on cost benefits, availability, and development of computer image analysis techniques.

General Interpretation Information

The key to successful conventional interpretations of vegetative cover on any photographic scale is the timing of the photographic data to take full advantage of phenological developments. For example, in the northern temperate zone, vegetation is best interpreted on CIR film in early spring before new deciduous foliage covers the ground and in the fall when deciduous foliage increases in IR reflectance (Hunter and Bird 1970). On high-altitude CIR film, the best time of year for forest type differentiation in the southeastern United States is from late fall, after the leaf fall, to early spring (Aldrich and Greentree 1972). Here, leafless conditions are important to differentiate between the upland and bottomland deciduous types. Moisture in the soil and in the humus layer absorbs IR radiation causing a dark blue response on CIR film taken over deciduous forests. Also, according to Hunter and Bird (1970), the drier the site the greater the leaf reflectance will be in the visible spectrum.

Another important but often misunderstood point is the effect of vegetation age on visible and IR reflectance. For instance, old leaves of deciduous trees reflect more energy than young tree foliage (Hunter and Bird 1970). Furthermore, reflectance from hardwood (deciduous) foliage decreases during early weeks of the growing season, remains fairly constant until after the middle of summer, then rises rapidly during the autumn color change. This explains why midsummer photographs show little discrimination between species. Variations in reflectance from deciduous foliage are minimized during autumn, and conifer foliage reflects significantly less energy toward the end of the growing season. This difference helps to accentuate the deciduous/conifer boundary line for type mapping.

Large- and Medium-Scale Photography

Vegetative cover classification.—Vegetative cover classification to the level of species composition could become more important as the cost of field data rises. Large scales would be needed to accurately identify and map individual tree and lesser vegetation in complex deciduous and coniferous associations found in the central, eastern, and southern United States. This use requires scales larger than 1:4,000. Normal color and CIR films are necessary to separate the individual species. Generally, normal color has proven to be best for tree species (Heller et al. 1966, Aldred 1976, Miller et al. 1976, Sayn-Wittgenstein et al. 1978) and, at the peak of flowering, CIR is best for grasses and forbs (Driscoll 1969, Driscoll and Coleman 1974). According to Tueller et al. (1972), all tree species, most shrubs, and some grasses and forbs can be accurately identified on 70-mm large-scale aerial photography.

There have been a number of developments for application of medium-scale BW, color, and CIR photography for vegetation classification and mapping during the past 15 years, including the use of 1:15,840 color photography by the USDA Forest Service. Aldrich and Norick (1969), using nonstereo

1:20,000 scale BW photographs, showed that post sampling stratification by forest type and volume could improve sampling efficiency on national forest surveys. Johnson and Sellman (1974, 1975, 1977) developed dichotomous interpretation keys in Alabama to aid stratifying forest cover into meaningful cover types on 1:20,000 BW photographs. They used slope and aspect as well as stand density, tree heights, crown widths, and tone as variables in their keys. For wetland mapping, CIR at 1:24,000 scale was found to be most suitable for delineating types down to a 2.5-acre (1.0-ha) minimum (Werth et al. 1977). In contrast, Scher and Tueller (1973) found that 1:10,000 color and CIR photographs exposed in late summer early in the morning were best for mapping wetlands in Nevada. For operational wetland mapping in New Jersey and New York, Brown (1978) found that a combination of 1:12,000 CIR and color films was best. Austin and Adams (1978) had a similar experience mapping marine plant resources. They found that color was most useful for definition of submerged vegetation to depths of 7 m. However, CIR and color together provided the best definition of above-water intertidal seaweed vegetation. A scale of 1:10,000 was used to map 11 vegetation communities.

Disturbances.—Detecting and mapping disturbances to the vegetative cover requires careful consideration of reflectance patterns more than any other user requirement. Water deficiency stress caused by insects, disease, or other agents must be detected and mapped on photographs that are timed to take advantage of foliage color changes. This means that CIR and color film must be used to capture the subtleties of color differences between healthy and stressed trees. The photographic scale depends on the ground resolution required (size of the trees or affected part). For example, white pine weevils (*Pissodes strobi* (Peck)) often only affect the terminal growth of seedlings and saplings and are accurately detected and counted only on 1:600 scale sample photography (Aldrich et al. 1959). Individual trees attacked and killed by bark beetles are detected on 1:7,920 or larger scale color or CIR film (Heller 1974). Heller also claims that if small infestations of one or two trees can be overlooked, a scale of 1:32,000 using CIR film is the most efficient. In 1976 a high resolution panoramic camera (Optical Bar; KA80A) was evaluated in a dead timber pilot study (Weber 1977). This camera takes photographs 4.5 inches wide by 50.26 inches long (11.4 by 127.7 cm). The results were encouraging enough to photograph 20 national forests in the western United States in 1978 at 1:33,000 scale with CIR film to assess the impact of forest insects. Regardless of scale, neither color nor CIR photography is useful as a previsual detector of bark-beetle-infested conifer trees. Although Colwell (1956) reported that stress caused by a disease in wheat could be detected previsually on CIR film, there has been no corroboration of this finding for either conifer or deciduous forest trees.

Aerial photographs have not been widely used as a tool to survey defoliators of either conifer or deciduous forests. This is primarily because defoliators are not as important or as serious a problem as bark beetles. Defoliators do not usually kill trees except over several years of repeated defoliation and the benefits usually will not justify the expense of photography. Visual survey techniques from an aircraft (Heller 1974) are more suitable to monitor these and other less important insect and disease problems. Special purpose sampling photography, however, can be beneficial for assessing defoliator damage both before and after control efforts (Wear and Curtis 1974). Furthermore, Ashley et al. (1978) found that 1:15,840 CIR photography in late summer could define forest with various stages of feeding stress, recovery, and mortality caused by spruce budworm (*Choristoneura fumiferana* (Clemens)) in Maine. The technique is considered feasible for locating stands of balsam fir and spruce needing salvage or presalvage cutting. In this example photography is justified by the followup management activity. Sometimes, however, sampling photography is easier to justify. For example, large-scale color photographs (1:1,584) could be a useful sampling technique in monitoring spruce budworm defoliation and its effects over time. Photographs taken annually for 10 years over several spruce-fir plots with varying degrees of spruce budworm defoliation in Minnesota not only showed the different levels of damage but were also helpful in measuring trends in the overstory and understory vegetation resulting from tree mortality (Aldrich and Heller 1969). Large-scale 70-mm color and CIR photography is a feasible method to measure tree losses and monitor change in a sampling framework. For example, the Northern Region (R-1) of the USDA Forest Service uses 1:2,400 color photographs to determine yearly mortality rates in deriving growth and yield estimates.[4]

Forest diseases are not as easily detected and evaluated as insect damage. There are three major reasons for this: it takes a long time for visible symptoms of disease to show up, symptoms are usually not uniform over the stand or forest, and most disease symptoms are far more subtle than insect damage. Therefore, not all forest diseases can be detected on aerial photographs. Those that are detectable with some degree of success are dwarf mis-

[4]*Conversation with D. A. Hamilton, USDA Forest Service, Forest Science Laboratory, Moscow, Idaho.*

tletoe (*Phoradendron* sp.), Dutch elm disease (*Ceratostomella ulmi* (Schwarz)), and oak wilt (Meyer and French 1967, Ulliman and French 1977), basal canker of white pine (Houston 1972), ash dieback (Croxton 1966), *Fomes annosus* (Fr.) Cke (Murtha and Kippen 1969), sulfur dioxide damage (Murtha 1973), and ozone damage (Wert 1969). Large scales of color and CIR film (1:1,584) are needed to assess the degree of damage, whereas 1:8,000-1:16,000 scales of CIR can be helpful in defining and delineating the boundaries of the disease. Again, 70-mm color and CIR photography used as a sampling tool within susceptible types can be useful in damage assessments (Lessard and Wilson 1977, Rush et al. 1977).

Disturbances to the vegetative cover caused by windstorm, flood, fire, or activities of man are relatively easy to detect on conventional aerial photography. Detection and measurement of the change, however, depends on having photography available for two points in time—a base year from which changes are to be measured and current photography. However, photographic coverage often is not available or too expensive to obtain. This and several technical problems make conventional photography difficult to use for change detection. According to Shepard (1964), there are five problems inherent with conventional photography for change detection: (1) noncoincidence of sequential flights; (2) differences in shadow direction on sequential flights; (3) clouds targeted as change; (4) seasonal differences in vegetation indicated as change; and (5) the requirement to handle different film sizes, types, and scales. Landsat MSS data collected from the same or nearly the same sun synchronous orbit at 9-day intervals would avoid some of these problems. This will be discussed in another section of this review. Conventional applications of medium-scale aerial photography for land use and cover-type mapping are well documented in text books (Spurr 1960, Avery 1977).

Nonvegetative cover classification.—Nonvegetative cover includes surface water and soils. The characteristics of lakes and streams and techniques for recreation inventories of mountain lakes are described by Herrington and Tocher (1967). To map the presence of water, CIR and IR films are preferred. Water absorbs IR radiation causing water pictured on IR films to be black and on CIR film to be varying shades of blue. The shade of blue representing water on CIR film is dependent on water depth, sedimentation, and other pollutants.

Probably one of the most effective and economical methods to detect small quantities of oil on water is photography in the near UV region (American Society of Photogrammetry 1975). Fast BW film with a Wratten 18A (W-18A) UV transmitting filter produces photography of the reflected UV energy. However, because of severe degradation by atmospheric haze, this film-filter combination should be flown below 1,000 m and only on clear days. The method is inexpensive and can be used with a 35-mm camera.

Standard BW medium-scale aerial photographs have been used in soils mapping since the mid 1930's. The photographs are used to relate different soils to different landscapes with the photographs providing information to draw soil boundaries. In this way, aerial photographs increase mapping rates and improve map accuracies. Current procedures used in national soil surveys are given in a Soil Conservation Service handbook (U.S. Department of Agriculture, Soil Conservation Service 1966); however, differences in color and tone of adjoining photos, and sometimes within a photo, caused so much confusion that color was not helpful. A more recent study by the Agricultural Research Service (U.S. Department of Agriculture, Agricultural Research Service 1975) in Texas, however, indicates that color and CIR photographs increase mapping rates and cartographical details, and the quality of maps was improved when compared with maps made from BW photography.

Mapping soils directly from aerial photographs has met with only limited success and then only in areas of low vegetative cover. Bare soils, according to Hunter and Bird (1970), have maximum reflectance variation in the 0.6-0.7 μm (red) portion of the EMS. Also, IR photographs give increased contrast between wet and dry soils and are superior for drainage maps. A combination of normal color film and IR film would appear to be best for soil-related information.

Small-Scale Aerial and Space Photography

The most important advance in the state-of-the-art in conventional photointerpretation during the last 15 years resulted from the advent of high altitude and space photography (9,150-24,390 m and over 242 km, respectively). For the greatest part, these advances were made possibly by greatly improved CIR films (CIR 2443 and CIR SO-127) which can penetrate the haze in the earth's atmosphere from both aircraft and space platforms. When used with haze penetrating filters, high definition BW and normal color films will also increase the interpreter's range of capabilities—if the photography is available or if it can be flown within budget restrictions. Small photographic scales provide essentially the same information obtained on medium-scale aerial photographs with only a slight decrease in accuracy (Ulliman and Meyer 1971). A major problem to be overcome with mapping on small scales is the limitation in legend recognition levels that can be used—the legend must

be less complex and delineations must be for larger minimum areas. Often features can be interpreted but, because they are too small, cannot be displayed on a map and are difficult to locate in the field (Marshall and Meyer 1978).

Vegetative cover classification.—Nielson and Wightman (1971) found that 1:160,000 CIR photographs were suitable for broad forest classifications and mapping in Canada. They found that differences between coniferous and deciduous species were striking and some further classification within these broad groups was possible (i.e., some species associations and individual species could be separated). The amount of information provided was sufficient to revise 1:15,840 scale forest-type maps. In a separate and unrelated study in Manitoba, Thie (1972) mapped an area of 6,000 square miles (15,553 km^2) on 1:60,000 and 1:100,000 BW imagery. This seemingly impossible task was accomplished in less than 1 man-year. The cost of large-scale mapping from 1:114,000 CIR was one-half the cost of mapping from conventional 1:15,000 BW photographs (Kirby and Eck 1977).

Range plant communities can be classified on both Skylab S190B color photographs and high altitude CIR photographs to the regional level of ECOCLASS (Daubenmire 1952) with accuracies acceptable for stratified inventory sampling designs (Francis and Driscoll 1976). Regional level classes (grassland and conifer) were correct over 90% of the time, and deciduous (aspen) was correct 80% of the time. Conifer and deciduous class accuracies were dependent on the date of photography, scale, and film type, whereas, grassland was less dependent on these variables. To stratify series-level plant communities, high-altitude CIR film was acceptable only if some classes were combined. The authors concluded that topographic slope and aspect, mountain shadows, ectones, season, and class-mixing adversely affect interpretation of plant communities in the Rocky Mountains.

The mapping of marsh, wetland, and aquatic categories of vegetated and nonvegetated cover on high-altitude aerial and space photographs has been documented in recent literature. On Skylab S190B photographs, visual interpretations resulted in distinguishing 10 vegetation and land use categories with 75-99% accuracies (Klemas et al. 1975). Forest, wetlands, water, and agriculture were classified almost without error. Three separate saltmarsh grass species were separated as were bare soils, sand, cropland, bare mud, and water. Using Skylab S190A photographs, Anderson et al. (1975) were able to accurately classify wetland types, delineate freshwater marshes, and make detailed analyses of drainage patterns.

Nonvegetative cover classification.—The use of high-altitude photography for soils mapping may someday replace current methods using medium scales. For instance, in Minnesota 1:90,000 BW photography has been acquired to use in statewide soil surveys to compile generalized soils maps (Rust et al. 1976). The authors report that the mapping rate was one township per day. Geomorphic regions were used to identify and isolate distinctive parent materials and topography on the photographs. Because information in high-definition BW photography is nearly the same as in conventional photography, it seems possible that these small-scale photographs can be used as a manual procedure for soils mapping with cost savings.

Despite efforts to dehumanize photographic interpretation, the human eye and brain still provide the best interpretation of aerial photographs. The technology of microdensitometry, however, if interfaced with the human brain, may increase the speed of classification and mapping processes in the future.

Interpretation by Film Density

Microdensitometry, or the measurement of optical film density and spatial characteristics of film emulsions, had its roots in the film manufacturing industry (Derr 1960). The application of microdensitometry to wildland resource inventory grew out of attempts by military and private research and development sectors to screen aerial reconnaissance films for military targets using pattern recognition techniques. Earliest attempts to digitize photographic transparencies by optical density specifically for resource inventories were done in the early 1960's (Langley 1965, Doverspike et al. 1965). These early works emphasized separating forest land from nonforest land and mapping forest to establish a base for forest inventories.

Microdensitometers in the early 1960's were slow (170-1,400 μm per second) and the output was usually on paper charts. Today, horizontal-stage automatic-scanning microdensitometers can scan at a rate exceeding 60,000 μm per second. A typical scan of a 9- by 9-inch (23- by 23-cm) aerial photograph with a scan line every millimeter would take 19 minutes to complete. A color transparency with three dye layers (red, green, and blue sensitive) requires three scans or about 1 hour to be completely digitized, recorded on computer-compatible tape, and ready for use in digital image analysis systems. The most useful digitized photographic data will be acquired from small-scale photography. Smaller scales cover larger ground areas, have fewer problems with image distortions, and result in a lower cost per acre for mapped

information. With some additional correction algorithms, image processing software developed for supervised and unsupervised classification of Landsat data can be used with digitized photographic data.

Forestry-related studies.—Several research studies were completed during the early 1970's using a Photometric Data System (PDS), microdensitometer (now Perkin-Elmer) and its companion operating system (Aldrich et al. 1970, Norick and Wilkes 1971, Greentree and Aldrich 1971, Aldrich et al. 1976). These research studies showed that optical density could be used to differentiate between many forest and non-forest land classes. Using Apollo 9 CIR transparencies (1:2,400,000), 13 land use classes could be separated; however, forest types could not be distinguished on density alone. The data suggested that it may be possible to develop signatures for forest types and other land-use classes using a combination of nine variables including density, density differences, and density ratios. It was shown, for a limited area, that film densities could be used with computer-assisted image analysis to separate land use and forest classes. For example, on Skylab S190B color photographs (1:500,000 scale), forest land was classified correctly over 80% of the time but with a 30% commission error. The implications are that forest cover and other land cover types may be estimated by sampling digitized data from future satellite coverage if high resolution CIR film is used and if a classification system is designed that is based on the land cover rather than the intended or current use.

Range-related studies.—Research in the application of microdensitometry to plant identification and yield studies has shown some limited success. In range studies image density differences in CIR aerial photos discriminated individual shrub and tree species of a pinyon-juniper plant community (Driscoll et al. 1974). In addition, image density was used successfully to identify six general plant communities: ponderosa pine, spruce-fir, aspen, big sagebrush, native grasslands, and seeded grasslands. However, there was no attempt to use signatures in computer-assisted classification. Von Steen et al. (1969) found a statistically significant relationship between certain preharvest yield indicators and densities of aerial CIR film. Although this was an agriculture study, the results suggest that in addition to classifying range species and types, optical density estimators may be developed for predicting productivity of range sites.

Unresolved problems.—Results of these forestry- and range-related experiments have been encouraging; however, much research is needed to resolve such questions as the best season and scale of photography as well as to improve feasibility by overcoming photographic variability for time of day, date, and atmospheric conditions. As Coggeshall and Hoffer (1973) stated, "although CIR aerial photographs would be cheaper and easier to acquire than aircraft scanner data, and photographs are easily interpreted manually, the narrower dynamic range of the film, the illumination problems within the photographic set, and the limitation to only three channels of data (red, blue, and green and thus only three dimensions in the computer classifier) seem to pose serious limitations to photo density analysis by ADP techniques—computer assisted image analysis—developed for MSS data."

The two largest problems standing in the way of relating film brightness contained in the three layers of color film to physical properties of a scene seem to be atmospheric interference and film exposure variables. Relatively small changes in sun angle and haze level have been found to substantially reduce classification accuracy using remotely sensed data (Potter and Shelton 1974). One way of reducing the effects of these variables is to use a ratio display method for image brightness variations (i.e., image brightness variations are expressed in the form of relative values or ratios) (Piech et al. 1977). This ratio display method was an effective and accurate approach to interpretation of spectral brightness differences contained in color film. Using the technique, metal, water, pavement, soil, cultivated fields (light vegetation), and vegetation (dark forest areas) were classified with an accuracy of 97% on 1:100,000 scale imagery.

Another approach to atmospheric interference and film exposure variability is through the use of sensitometric analysis. Although sensitometry will be more difficult to implement, this procedure should, in the long run, reduce the problem of diversity between color and CIR photographs taken by a variety of cameras, filters, and film emulsions under different lighting and atmospheric conditions. This approach will require an accurate and reliable sensitometry program—a capability of calibrating film optical density against effective exposure (Dana 1973). Research in this technology should continue while methods such as ratio display of brightness variations are implemented in operational studies.

INTERPRETIVE INFORMATION FOR SPECIFIC APPLICATIONS

Interpretive information is collected to monitor environmental disturbances, trends in wildlife habitat, and geologic hazards, and to chart geologic

structures and locate and assess archaeological finds.

Detecting environmental disturbances.—The impact of natural phenomena and human activity upon the vegetative, soil, and water resources can be monitored using aerial photography. Sometimes aerial photography can be used as a followup to verify and describe phenomena detected by non-photographic remote sensors. This would be particularly cost beneficial if Landsat MSS data were used to screen an area for suspected anomalies. The choise of methods to use in a surveillance system will depend on cost, the amount of detail needed, and availability of photographs, Landsat data, maps, and equipment.

To determine the human impact on roadway environments, an inventory could be made using ground techniques or one of two aerial photo techniques (Potter and Wagar 1971). If the view from the road is important, then a ground surveillance technique is appropriate. If, however, the need is to determine the location of existing powerlines and manmade developments, then an aerial photographic technique can be quite adequate. CIR and color films have major advantages in assessing human impacts because of the increased differentiation they provide among small variations in the ground objects. However, the added cost is not likely to be justified unless the photographs are already available.

Tree condition within municipal limits or within high value areas such as campsites or parks may be monitored on aerial photographs. For example, trees affected by smog can be detected on 1:8,000 color film but to rate the damage, a 1:1,584 scale is needed (Wert et al. 1970). The timing of photography is important to accurately assess the damage. In southern California, December was the best month for assessing damage to ponderosa pine needles. The films and scales required for other more apparent tree damage symptoms were discussed under Classification and Mapping in this review. Also, Murtha (1969) has put together a bibliography for interpretation of forest damage, which is close to the state-of-the-art. He has also assessed vegetation damage problems and makes appropriate recommendations for solutions (Murtha 1976). An overview of techniques for forest insect damage surveys is also given by Heller (1974).

Remote sensing of the impact of grazing animals on stream and meadow ecosystems has been reported by Hayes (1976). In his technique for appraising grazing impact, Hayes used a 70-mm camera and CIR film. He found that 1:2,000 to 1:8,000 photographs will provide resource analysts with a method for observing the influence of management systems on stream-meadow complexes. The photographs provide a vegetal stratification and identification and a base for further observation of vegetative change—range condition and trends. Stream channel stability and alterations can also be monitored. CIR photos at 1:600 to 1:1,000 scale were an aid in detecting differences between grazed and ungrazed areas within a single vegetative complex. Fecal matter could be recognized on 1:2,000 scale photography.

Wildlife habitat.—To monitor wildlife habitat trends and related vegetative and hydrologic changes, Scheierl and Meyer (1977) found a 35-mm photography system beneficial. They used both CIR and color at a 1:8,000 scale. Color film was most useful for aquatic plant detection, species differentiation, and enhancement of shrub differentiation. Color combined with the CIR enabled detection and differentiation of upland vegetation with optimum results. They recommend using plant indicators for establishing the optimum time of year for photography.

In another closely related study, Greentree and Aldrich (1976) found that 70-mm photography was useful for monitoring stream trout habitat conditions. They found that most characteristics of trout streams are visible and easily described directly on the photographs. Habitats supporting trout stream insect production can potentially be evaluated using the photographs as a base from which to sample and collect the biological data. The best overall scale and film for evaluating streambank conditions is color at a 1:1,584 scale. CIR film is best for evaluating low grassy areas with undercut banks and where healthy aquatic vegetation is found.

Geologic structure and hazards.—Geological hazards such as damage resulting from earthquakes, including seismic seawaves along coastal areas, landslides in areas of unstable slopes, and subsidence and flowage of surface materials in areas underlain by sands and clays in various stages of water saturation are interpreted from aerial photography (Pestrong 1971). The author also points out hazards associated with surface water, including flooding along streams and rivers, erosion and gullying of certain slopes, and standing water hazards in areas of poor drainage, can be detected on aerial photographs. Because of the economic consideration, however, the principal film used for interpretation is BW. He goes on to say that CIR photographs would be more useful because of the subtle shades of hue and saturation that are important in addition to form and shape. The CIR will show landslides disrupting drainage and vegetation more clearly than other films.

According to Hunter and Bird (1970), IR photographs are particularly useful in geological interpretations because surface configuration and textural patterns on exposed bedrock are emphasized by shadows and moisture in depressions. However, to find outcrops underneath vegetation requires 1:4,000 color taken under an overcast sky (Myers 1975).

The application of remote sensing including aerial photographs, Landsat, thermal scanners, and radar for landslide hazard interpretation is covered by Gagnon (1975). Hazards are defined by Gagnon as slips, slumps, and clayey outflow (liquefaction). Slip and slump are controlled by slope, and clayey outflow is affected by ground water table, saturation, drainage, infiltration, and vibration. Color photographs have advantages for soil color and identification, and for detection of thin organic material, infiltration lines, and sand-silt cover. BW IR is important for water and soil moisture analyses. For example, ground water table, saturation zones, high water content surface materials, seepage lines, surface drainage, saturating water bodies, and infiltration lines must be checked with this imagery. CIR photographs can provide surface drainage, infiltration lines, and ground water mainly through vegetation analysis. However, CIR does not add significantly to the information available on BW IR.

Archaeological applications.—Archaeology, probably more than any other science, fully utilizes aerial photographs to interpret sites based primarily on associations. Detection and evaluation of most archaeological sites is made possible by recognizing certain factors in obtaining photographic data. One of these factors is that drier seasons of the year are preferred over wetter periods because the loss or retention of moisture by various soils provides more striking tonal contrasts (Lyons and Avery 1977). In areas of high humidity, aerial photography for archaeological application should be done during the leafless period. However, there really is no single period of the year that is best for all forms of archaeology. If shadows are important, photographs should be taken in the early morning or late afternoon, when the sun is low. Midday sun is best to minimize shadows, to gain the best illumination of terrain features, and for good color rendition.

The film type and scale of photography most useful for archaeology vary. However, there is agreement that color is better than BW for most work and that CIR is preferred for delineating subsurface detail such as shallow buried foundations (Lyons and Avery 1977). Both color and CIR are better than BW for detecting soil marks and certain crop or plant marks. Since BW IR has been found useful for locating buried pipelines, it should be investigated for archaeology. According to Lyons and Avery, 1:10,000-1:20,000 scales have been successful; however, the literature indicates that 1:3,000 to 1:10,000 scales are preferred. Multiband photographs are preferred by Whittlesey (1972) because they increase the capability to detect archaeological sites by comparing various film/filter combinations simultaneously for the same area.

MEASUREMENTS OF RESOURCE PARAMETERS

Direct field measurement is the only substitute for a stereoscopic pair of vertical aerial photographs to measure parameters of the forest and other wildland resources. Combining field and photo estimates can be 6-15 times more efficient in estimating commercial forest land area than is using field plots alone (MacLean 1963). Volumes obtained by photo measurements and photo volume tables reduce field survey time about 60% (Moessner 1963) and double sampling for stratification provides estimates of total volume twice as efficiently as does simple field plot sampling (MacLean 1972). Much of what we know today about photo measurements is the result of work by early forest photogrammetrists such as Moessner (1949, 1960, 1961), Rogers (1946, 1947), and Spurr (1945, 1948). Avery (1977) and Spurr (1960) give complete instructions on how to use aerial photographs to measure area, height, crown closure, and crown diameter, and how to relate these measurements to stand size, site, and volumes. Publications with specific applications of aerial photographic measurements are annotated by Nielson (1971).

The mensurational aspects of resources, other than forests, are generally restricted to determining areal extent of delineated soils, landform, and plant communities. The scale of aerial photographs and topographic relief have a great affect on the accuracy of these measurements.

Mensuration.—Improvements in photographic techniques for mensuration have come by way of larger scale photography, more efficient sampling designs, and improved measurement instruments; the basic concepts and techniques have remained the same. For example, large-scale, 70-mm photography using color, CIR, and BW positive transparencies, contact prints, and enlargements opened up a new information source for resource inventories and resource monitoring. Tests of large-scale sampling photographs as early as 1962 (Sayn-Wittgenstein 1962) showed that they would play an important role in future forest surveys. He cautioned, however, that before reliable measure-

ments could be made, certain important problems needed to be solved, not the least of which was scale variation. One way of handling the scale problem was by using a fixed air-base and two cameras from a helicopter (Lyon 1967). With a fixed air-base the flying height above ground could be calculated and mean height measurements made within ±3 feet (0.91 m). The cost was only 15% of the standard survey cost for rather remote areas of British Columbia.

Another way to overcome the problem of scale variation inherent in large-scale photography was developed by the Canadian Forestry Service. This development was a radar altimeter specifically to fit the needs of forestry (Nielson 1974).During the large-scale photographic mission,the altitude above ground is printed directly on the film. Nielson (1974) reports that vegetation is completely penetrated and the accuracy of flying heights is within ±1% of the actual altitude. In typical mixed conifer and hardwood stands in Canada, tree heights were made within 3.5 feet (1.07 m) and crown diameters within 2 feet (0.61 m) (Kippin and Sayn-Wittgenstein 1964). No more than 4% of the trees were missed. This radar system is now available commercially.

For timber volume estimates, large-scale photographs require that the stand approach be abandoned in favor of precise examination of samples of individual trees (Aldred and Kippin 1967). By examining individual trees and measuring the variables of total height, crown width, crown area, proportion of tree crown overlapped by crown of another tree, and other expressions of a tree's position in relation to its neighbors, the contributions of each toward reducing the residual sums of squares was determined in a stepwise regression (Sayn-Wittgenstein and Aldred 1967). The most useful variables were direct measurements of the trees. Expressions of position of a tree in relation to its neighbors—the crowding or competition factor—were less important.

When large-scale 70-mm sampling photography is used in tropical forests, the specifications are somewhat different than photography in the northern boreal forests. Aldred (1976) recommends that the most accurate measurements are made on positive color film transparencies at scales of 1:2,000-1:4,000 taken under an overcast sky. These same specifications are optimal for tree species identification except that larger scales would probably produce the most precise results, although at probably an unacceptable cost.

In recent years there have been two large area operational timber inventory trials using large-scale aerial photographs—one in Nova Scotia (Bonner 1977) and the other in Alberta (Aldred and Lowe 1978). Both inventories provided the required forest statistics close to specified limits of accuracy. In both examples the photo method was found to be most cost effective when applied to inventories of large, relatively inaccessible areas that sometimes require the use of aircraft for ground access. In Alberta 100-500 plots would be required before the photo method would pay off.

Range inventories require a measure of the cover percent of grasses, forbs, and shrubs. Large-scale aerial color and CIR photographs can be used to measure percent vegetative cover from recognizable species in a significantly shorter time than conventional field methods using larger sample sizes (Tueller et al. 1972). However, the density (number of plants per unit of area) cannot be extracted for most species.

Water measurements.—Herrington and Tocher (1967) describe characteristics of lakes and streams that are measurable on aerial photographs. These measurements are important in recreation inventories of mountain lakes. The depth and quality of water is also important in water resource inventories. According to Helgeson (1970) reasonable increases in the apparent depth or distance penetration of masses of water may be accomplished by sensing the proper region of the EMS. He goes on to say that properly displaying the remote sensing record will enhance the use of the dynamic density range of the material. He describes and recommends a multilayer photographic material—either bicolor or tricolor—in bands properly selected to take advantage of spectral absorption and scattering properties of water. The choice of bands should be based on the spectral differentiation required for bottom detail.

Water quality indicators are also important in classifying lakes and streams. Bartolucci et al. (1977) found by in situ measurements that differences between turbid and clear water are most apparent in the 0.6- to 0.9-μm region of the spectum or within the sensitivity of CIR film. They also found that river bottom reflectance characteristics have no influence on the water reflectance characteristics when the water is over 30 cm deep. Schutz and Van Domelan (1975) present several theoretical equations to use in computing and describing physical relationships, bottom effects, effects of oil slicks, turbidity, and algae. They describe how backscatter of different wavelengths change with the type of material in the water. Thus, each type of material has a unique spectral backscatter "fingerprint" which allows them to be identified. For instance, they have developed curves to "fingerprint" distilled water, clear Lake Superior water, taconite rock flour, moderate red clay, and heavy algae. These and similar signatures can be useful in application of both aircraft and Landsat images for classifying

lakes. There are pitfalls, however, in applying signatures beyond the immediate area for which they were developed.

Sand movements.—Movement of sand is important in managing coastal zones. Vegetation is the best know precipitator of sand accumulation. Aerial IR photography has been used to detect the topographic changes in vegetation-induced sand dunes of the North Carolina outer banks (Stembridge 1978). The high IR reflectance produced by the mutual interdependence of precipitator dune vegetation and windblown sand accumulation makes it possible to predict dune growth and deflation pattern in vegetated coastal dune systems.

OBSERVATIONS AND COUNTS OF OCCURRENCES

Observations required by USDA Forest Service users of remote sensing data include buildings and structures, water structures, transportation, recreation, and wildlife. With the exception of recreation and wildlife uses, it is highly unlikely that special-purpose remote sensing will ever be justified. As recreational and wildlife management activities increase, however, special-purpose remote sensing may be required to monitor human activities and their effect on the wildland resource and wildlife populations (big game). Other observations will be made from available photography or from aircraft.

Manmade structures and developments.—Studies to determine the accuracy of observations using aerial photography are extremely rare. Most information related to manmade structures and developments must be taken from references to urban and regional surveys of land use and other studies by geographers.

Geographers have found that high-altitude photography (1:120,000) can be used to prepare urban land use maps to a 1-ha minimum (Simpson 1970a). These maps are prepared with 24 different categories and usually to a 4-ha minimum to compare with Landsat data. Simpson (1970a) also says that CIR transparencies are particularly useful for urban land use identification, delineations, and for urban change detection.

In Los Angeles 1:60,000 scale aerial photography was found useful in urban studies (American Society of Photogrammetry 1975). This scale was most helpful to provide extensive coverage of a city and its immediate surroundings. However, 1:20,000 scales permitted identification of city sections with greater detail and 1:5,000 was most appropriate to study individual properties. Good quality 1:60,000 photographs can be enlarged to 1:20,000 and 1:5,000 without loss of resolution and provide necessary information at the individual property level.

Generally speaking, to detect and evaluate structures and transportation, communication, and utility systems, and to count vehicles and other items within a wildland environment requires photographic resolucapabilities ranging from 0.3 to 15 m. Although in most instances available photography will be used, CIR will have the greatest utility.

Recreation and wildlife management.—Aerial photographs could be advantageous for both recreation and wildlife census because they capture a scene instantaneously on a piece of film for later study. Ski slopes, parking lots, boats, marinas, and the wakes of boats are discernable even at 1:120,000 scales. However, accurate counts of vehicles and people will require much larger scales. People counts will require at least 1:2,000 scale or 0.1-m resolution. Large-scale 70-mm aerial sampling photography over recreation sites could be useful for monitoring recreation use impact.

Aerial photographs could be used for animal census particularly when the animals group together in the sunlight. However, aerial films see approximately the same scene that the human eye can see. Therefore, if the animals are camouflaged on the ground, they will also be invisible on film. Another limitation is the need for optimum weather and bright sunlight (Parker 1971). This is because deer often seek cover during the middle of the day when picture taking is best.

Probably the best example of the use of aerial photography for animal census is a livestock inventory made in California (Huddleston and Roberts 1968). In this and previous studies, a scale as small as 1:5,000 could be used as a sample with consistently high accuracies. BW film was most acceptable from a cost and effectiveness standpoint. However, color transparency film gave the best accuracy, particularly for identifying the animal type and breed. A W-12 filter used with BW film increased the contrast and haze penetration and darkened the shadows to give a more interpretable image. Huddleston and Roberts (1968) found that the best season for inventories was early spring after the winter rains but before shallow soils dried out and caused vegetation to brown up. The best time of day was a few hours after sunrise and a few hours before sunset, when animals were not seeking shade. However, aerial photographs are limited in that livestock are not detectable under manmade or dense natural covers. Simultaneous ground enumeration must be made to develop corrections for bias in the image counts.

In an unusual application of aerial photography, harp seal pups were found detectable by UV photography (Lavigne 1976). Standard BW film registers only dark-colored adult harp seals on ice. With a special lens and film sensitive to UV rays, white costal pups were detected against the white background. The pup's fur absorbs much of the UV in sunlight. So does the polar bear; however, the arctic fox and hare tend to reflect UV light. Snow and ice also reflect UV. Thus, with the special lens (with UV filter) and film, a pup is registered a black image on a white background.

THE STATE OF REMOTE SENSING APPLICATIONS—NONPHOTOGRAPHIC DATA

The use of data from nonphotographic imaging devices has increased by leaps and bounds during the past 5 years. The advent of Landsat-1 in 1972, the Skylab Earth Resource's Experiment Package (EREP), and Landsat-2 and Landsat-3, has provided investigators with relatively low-cost data. Data are available on computer-compatible tapes and in electronically reconstituted photographic products. At present, MSS data are used more often than any other nonphotographic data for classification and mapping. Thermal and radar data are used less frequently to monitor resource conditions.

CLASSIFICATION AND MAPPING

Both computer-aided and conventional photointerpretation methods are used to analyze data from nonphotographic devices. Computer-aided classification using digital data stored on computer compatible tapes is generally considered the best approach in classification and mapping. Even though the spectral data are relative values and have been affected by atmospheric conditions, data are calibrated (system corrected) when recorded. The digital format provides the user great flexibility in analysis techniques. Photographic products can be made from the recorded data but the products are sometimes degraded to a certain extent in the photographic process. However, digital data often can be processed to enhance edges or scene contrast and to digitally enlarge the data in the photographic product (Rohde et al. 1978). Both computer-aided and conventional interpretation are discussed in the following sections.

Airborne Multispectral Scanner Data

The uses of airborne MSS in wildland resource management have been restricted to a few experimental applications in vegetative cover mapping, detecting disturbances, and nonvegetative cover mapping. From a technical point of view, airborne MSS can provide spectral and spatial resolutions to accurately map wildland resources. However, there are many operational problems still to be solved and costs of data acquisition and analysis must be reduced to be competitive with aerial photography.

Vegetative cover classification.—Early studies in vegetative cover classification using airborne MSS data for forest species discrimination were relatively successful. They usually looked at homogenous plantation-like forests under intensive management where positive results were most likely. One such study was made on an 80-acre (32.4-ha) experimental forest in Michigan (Rohde and Olson 1972). MSS data from six spectral regions between 0.4 and 1.0 μm were used in a computer-aided classification procedure. Coniferous tree species were discriminated from broadleaved trees, and sugar maple, black walnut, black locust, red oak, and white oak were successfully separated from one another. Discrimination between conifers was not as successful although spruce was consistently separated from pine. Overall accuracy, under these ideal conditions, was 85%.

Results of the first attempt to classify and map forest and other land cover classes on a wide area basis under natural conditions were rather discouraging (Weber et al. 1972). However, the test results did provide some leads for further research. For instance, the test indicated a need for an improved algorithm for applying corrections to the MSS data for sun angle and atmospheric interference and an improved sun sensor to measure irradiance during MSS flights. In addition, map quality and accuracy of point locations was poor as a result of uncertainties of aircraft altitude and velocity changes. One bright point from the study was the isolation of four channels of data that were most successful for classifying land cover in the north central Georgia area—the visible red band, two near IR bands, and one thermal band. These bands are very similar to recommendations made by Coggeshall and Hoffer (1973).

Airborne MSS data have been processed to map biomass in shortgrass prairie vegetation (Pearson et al. 1976). Results of image processing of these data were compared with actual ground-measured biomass values taken at the same time. The image processing prediction was 1.15 times the actual biomass with a correlation coefficient of 0.98 for 26 biomass ground truth areas.

Disturbance.—Another application of multispectral data that received a great deal of attention during the late 1960's and early 1970's was detection

of change in physiologic structure of trees under moisture stress (Weber and Olson 1967, Olson and Ward 1968, Olson 1972). Although there is good evidence that physiological changes occur in trees under moisture stress, it has been difficult to show evidence of this on remotely sensed data until after the trees are dead and the foliage has changed color. Bark-beetle-attacked trees are dead or beyond saving (but salvageable) once the tree foliage has turned color. By this time it is usually too late to prevent additional trees from being attacked. Previsual detection of trees under stress would be helpful to forest biologists in controlling the insect and disease outbreaks by silvicultural or other management procedures.

When airborne MSS data were tested for both visual and previsual detection of stress caused by root rot fungus (*Poria weirii*), mountain pine beetles (*Dendroctonus ponderosae* Hopk.), and oxidant air pollution damage, the results were discouraging (Weber and Wear 1970, Weber and Polcyn 1972). Incipient root rot infections in Douglas fir (*Pseudostuga mensiesii* (Mirb) Franco) could not be successfully identified using either multiple-channel processing in the 0.4- to 1.0-μm and 1.0- to 5.5-μm portions of the EMS or single-channel processing in the thermal data channel (8-14 μm). Oxidant-injured ponderosa pine in southern California could be discriminated by condition classes best in the 0.55- to 0.70-μm range of MSS data. However, the range of temperature difference between condition classes was too narrow and the data overlapped too much for accurate classification of thermal data. The greatest benefit MSS scanning could provide forest biologists, according to Weber and Polcyn (1972), would be previsual detection of stress in bark-beetle-infested trees. Working with three spectral bands (0.4-1.0, 1.0-4.5, and 8.2-13.5 μm), they were able to show very little evidence of previsual detection. However, with the availability of simultaneously registered data (not available at the time) covering the entire broad-band width in narrow band increments, large improvements in the results could be expected. At the present time, however, there is no evidence that MSS's are feasible for insect and disease survey.

Nonvegetative cover classification.—Soils mapping from remotely sensed data is most difficult where the land is covered by vegetation. Often a lack of correlation between current vegetation and soil class (Johnson and Sellman 1975) makes soils mapping more difficult. Where the soil is unvegetated, however, classification of soil by remote sensing has been more successful (May and Peterson 1975). Their study compared signatures for several Pennsylvania soils corrected for solar and atmospheric interference with signatures derived from MSS data in supervised and unsupervised computer classification routines. They found that the laboratory-derived signatures could be substituted for MSS signatures with only a slight decrease in accuracy. Computer-derived maps were similar to maps made by field surveys and were in agreement 90% of the time. According to Westin and Frazee (1975), using Landsat photographic data as a background in soils mapping greatly enhances information that can be deduced about hydrology and land use. They also found that color composites were adequate for locating most boundaries between soilscapes.

Special considerations.—Although it is ineffective from a cost standpoint today, MSS data from airborne platforms could provide spectral and spatial resolutions to accurately map wildland resources. Classification accuracy is highly dependent on the number of channels of data used and the portion of the EMS from which the channels are selected. According to Coggeshall and Hoffer (1973) the most cost-effective use of MSS data would be to use no more than five bands of data (over five bands results in very little improvement in classification accuracy at an increased cost) and at least one band should represent each part of the optical spectrum—two visible, one near IR, one middle IR, and one thermal IR. In this way classification accuracies of over 90% can be realized.

Variations within forest land can result in classification errors using MSS data and computer classification procedures, and these errors are difficult to account for. The reliability of feature signatures is dependent on the relationship of each signature to all others in the set (Sadowski and Sarno 1976). Signatures that compete with or statistically overlap neighboring signatures produce low classification performance because a large number of pixels are misclassified. Thus, signatures with small variance and high correlation may have an advantage over signatures with large variances and/or lower correlation. Multiple signatures might be used to characterize nonuniform areas within a feature to produce signatures of smaller variation and improve classification results.

When the spatial resolution of MSS data is degraded from 2 to 64 m^2, the overall classification of MSS data is improved (Sadowski et al. 1978). This improvement is attributed to a reduction in scene variation inherent in the averaging of information over large ground areas. There was 100% increase in the accuracy. This implies that there is substantially better classification performance for more generally defined features and that resource managers should be advised to avoid discriminating features that are too specific when processing MSS data by conventional procedures. Furthermore,

multielement classification rules provide for averaging information over larger areas, which is somewhat analagous to coarsening the resolution. For instance, averaging over nine elements (pixels) could be advantageous to improve the classification of detailed features that may be needed in resource inventories using coarser resolution satellite data.

Landsat Multispectral Scanner Data

Contrary to recommendations derived from airborne MSS studies (Coggeshall and Hoffer 1973), Landsat-1 and Landsat-2 MSS's were designed with four bands: two visible bands (0.5-0.6 μm, green; 0.6-0.7 μm, red) and two near IR (0.7-0.8 and 0.8-1.1 μm). A thermal band was added to Landsat-3 that covers 10.4-12.6 μm of the EMS. After geometric corrections based on U.S. Geological Survey (USGS) 1:24,000 map controls, or their equivalent, the geodetic error of a Landsat image is $<$1.0 pixel (57 m) and the temporal registration error between two images having the same World Reference Frame Numbers is only $<$0.5 pixel (28 m) (National Aeronautics and Space Administration 1978). World Reference Frame Numbers are used in a Landsat Worldwide Reference System (WRS) to locate centers of individual scenes. Reference numbers are defined by intersections of 251 Landsat ground tracks and 248 rows.

Vegetative cover classification.—One of the earliest and most comprehensive studies of Landsat data for land cover classification was conducted by the USDA Forest Service, in cooperation with NASA (Heller 1975). After 24 months of study Heller summarized that Landsat was primarily a source of first level information for multistage inventories of forest and range resources. Aldrich et al. (1975) and Driscoll and Francis (1975) reported that forested land could be separated from nonforest and water regularly with 95% accuracy and that forest and grassland were separable at the regional level of ECOCLASS (Daubenmire 1952) 92-99% of the time. However, when separations at lower levels in classification hierarchies were attempted, the level of accuracy dropped significantly below what was acceptable.

In a study of rangeland classification in southern Idaho, Hironaka et al. (1976) found that sagebrush stands could be separated from cheat grass on spring season imagery because of high reflectance from rapidly growing grasses. Such separation was not possible later in the season. They had only limited success in identifying ranges cleared and reseeded to crested wheat grass, probably a result of low IR reflectance caused by a high percentage of bare ground present in reseeded range. Success in identifying native range types depended on rainfall, amount of vegetative cover, and season of the year. Enlarging Landsat photographic images separated by four or five passes would permit managers to monitor conversion of rangelands to cultivated and irrigated crops and locate and measure the extent and configuration of burns in sagebrush-grass range.

Some of the more advanced techniques for interactive Landsat and photographic data sources were developed for the Large Area Crop Inventory Evaluation (LACIE), a joint project of the USDA, NASA, and the National Oceanic and Atmospheric Administration (NOAA). One development, known as procedure 1, was applied to rangeland classification (Reeves 1978). Procedure 1 is a computer-aided processing technique developed to optimize ADP and to minimize analyst processing time. The procedure uses a 117-line (row) by 196-picture element (pixel column) image area of Landsat digital data called segments. Aircraft data are required and classification success depends on the assumption that rangeland, nonrangeland, forest, nonforest, and water can be differentiated on aircraft photos with no significant error. It also assumes that shortgrass prairie, saltgrass, hardwood, and softwood can be differentiated on aircraft imagery with no significant error. The aircraft photos are used to establish probability of correct classification and to evaluate the Landsat classification results. The procedure produced accurate rangeland classifications, but short prairie grass and saltgrass could not be differentiated on the aerial photographs; therefore, these classes could not be separated in the procedure.

The use of Landsat MSS data in computer-assisted classification of wetlands is not as well documented as wetland mapping by conventional photointerpretation. This could be because many wetland areas are too small or too narrow for detection by Landsat or it may be because water absorbs IR and, therefore, is in conflict with IR reflected from vegetation. Nevertheless, there has been some success using Landsat data for general classifications, boundary definition, and monitoring human impact on wetlands (Anderson et al. 1975). In coastal zones, Klemas et al. (1975) found that a human-assisted approach to automated classification correctly classified ten categories of vegetation and land use with over 80% accuracy. Later, Klemas and Bartlett (1977) found that conventional computer-training techniques using relative radiance values for the different categories gave slightly better results than training signatures developed from in situ measurements of target radiance (85% versus 81%). They also found that variability of spectral reflectance in wetland areas is symptomatic of physical characteristics of the cover types (i.e., time

elapsed since tidal inundation of mud, plant height, and growth form).

Excellent treatments of the processes followed in computer-aided vegetative cover classification using Landsat digital data are provided by Hoffer and Fleming (1978) and Rohde (1978a).

Generally speaking, the accuracy of land cover classification is improved when two or more Landsat image dates are combined. However, very careful selection of the image dates is important. For example, in Canada, Kalensky (1974) used 12 channels of data representing 3 different dates (4 channels each date) and compared the classification results with 4 channels recorded on 1 date. The accuracy for the single-date classification ranged from 68% to 81%. For the multidate maps the accuracy increased to over 83% for agriculture, coniferous forest, and deciduous forest classes. In another, related study in the North Carolina coastal region, Williams and Haver (1976) had similar results, combining data for two Landsat scenes (winter and summer). The two scenes were analyzed individually, registered, and merged into eight channels of data to take advantage of temporal changes in the forest canopy. The best results were obtained from the combined data. Delineations of hardwood and pine categories and clearcut acreages were over 94% correct. However, the best separation of hardwood and pine was on winter data. Summer data allowed separation of pine into categories based on crown closure. Multidate images must be accurately registered pixel to pixel or many changes will be missed and some will be false calls. Accurate registration is the product of geometric corrections and must be within ±0.5 pixel to be effective. The new process for geometrically correcting Landsat data tapes at Earth Resources Observation Systems (EROS) Data Center (EDC) should fulfill this requirement when fully operational.

Large-area demonstrations of vegetative cover classifications.—Good quality photographic data produced electronically from Landsat computer-compatible tapes can be used with conventional photographic interpretation in large-area resource inventories. For example, a random-systematic double sample was used to estimate deciduous and coniferous forest area in nine counties in northern Virginia coastal plain counties (Aldrich and Greentree 1977). For deciduous and coniferous areas the sampling errors were 3.7% and 6.7%, respectively (at the 0.67 probability level). Total forest area was <1% different from the Forest Survey[5] estimate. Although the Landsat technique resulted in sampling errors 2-3.5 times larger than sampling errors for an operational inventory, with improved techniques for electronic enhancement and geometrically correcting Landsat photographic products such as those now available at EDC, these errors could be reduced considerably.

Recent literature cites several examples of the application of Landsat-1 and Landsat-2 data to land classification and forest mapping on large-area inventories using computer-aided techniques (Dodge and Bryant 1976, Krebs and Hoffer 1976, Roberts and Merritt 1977, Oregon State Department of Forestry 1978, Harding and Scott 1978). These examples have several things in common: (1) Landsat MSS data were used to stratify land classes by vegetative types, (2) computer-assisted classification was used in preference to conventional photographic interpretation, and (3) acreages of forest land and vegetation types were computed. Landsat classification accuracies for both forest area and forest type statistics were usually based on comparisons with Forest Survey Statistics for the most recent inventory. In most instances, these estimates were within ±10% for forest area and within ±25% for forest type.

A resource inventory in the San Juan National Forest in Colorado produced a forest cover map made from Landsat MSS data in combination with high-altitude CIR photographs and ground truth (Krebs and Hoffer 1976). Geomorphic features were manually interpreted and mapped from Landsat photographic data. Slope and aspect were interpolated from elevational data on Defense Mapping Agency (DMA) tapes of 1:250,000 USGS topographic map sheets. The topographic data were developed into 64-m grid cells and overlayed onto the Landsat data classified by a modified clustering technique using computer-aided classification. The modified clustering technique required less computer time to develop training statistics and produced statistics yielding higher classification performance. Vegetation-type maps within certain topographic positions could be produced with an accuracy of 84% at generalized levels (broad) and 80% at the community level (narrow). USDA Forest Service personnel in local management and land use planning activities considered the map as good or better than maps produced by conventional photographic interpretation techniques at a much higher cost.

In the conduct of national renewable resource inventories it is important to have accurate area estimates of forest land and forest types. Roberts and Merritt (1977) using a 17% sample of Landsat-2 data for a nine-county area in the northern coastal plain of Virginia and a combination of unsuper-

[5] *The Forest Survey was authorized by provisions of the McSweeney-McNary Act of May 22, 1928, as amended by the Resources Planning Act of 1974. Forest Survey units are now known as Renewable Resources Evaluation Units and are organizationally under the Division of Forest Resources Economic Research, USDA Forest Service.*

vised clustering and supervised classification algorithms, produced a forest area estimate less than 1% different from the Forest Survey. By individual counties the area differences ranged from 3% to 21%. Water was classified correctly 98% of the time. There was no reliable comparison for conifer and hardwood acreages. However, these and similar results using manual interpretation techniques indicate possibilities for Landsat data as first-level information in national, regional, and state renewable resource inventories.

A demonstration project conducted by the Oregon State Department of Forestry (1978) utilized Landsat for forest condition mapping and a forest volume inventory in Douglas County, Oregon. Products were color-coded maps produced at 1:125,000 with 9 generalized vegetation classes and at 1:62,500 with 24 vegetative treatment classes. Acreages were summarized by treatment opportunity group—conifer, conifer/hardwood, hardwood, hardwood/conifer, nonstocked forest, nonstocked other, and water by ownerships. Summaries were made of acreages by treatment opportunity groups, crown closure, and tree diameter classes for ownerships. Volume and standard errors were based on photo/ground estimates weighted by Landsat defined selection probabilities but without corrections. Volumes and areas from conventional inventories by government agencies and industry were compared with the Landsat estimates. The general conclusion was that statistics generated by the project were not usable and that additional refinement is needed before remote sensing statistics are reliable and can be used by management foresters.

A similar inventory was conducted in the State of Washington by the Department of Natural Resources but for a much larger area (Harding and Scott 1978). Nine Landsat scenes were selected to cover the entire western Washington project area and supplied the data base from which sample plots were located. Sampling was reduced to a minimum by stratification with Landsat data and the use of a multistage sampling design. Landsat coordinates of selected sample pixels were used to compute Washington state plane coordinates which were, in turn, used to plot secondary sample units on orthophotos and maps and eventually aerial photographs. A high degree of accuracy in relating pixels to ground locations was essential to the overall accuracy of the inventory. The secondary samples were transferred to aerial photos to an accuracy of 100 feet (30.50 m) with one-half the samples within ± 50 feet (15.25 m). However, since the equation for transforming Landsat coordinates to Washington state plane coordinates was accurate to only ± 1 pixel, the overall accuracy was not better than this. The study provided basal area by ownership class within ± 10% (0.95 probability level). In summary, the Landsat inventory process could be cost effective when and if the development work has been completed. Landsat can supply accurate data and there are adequate computer systems to handle the data, but software and procedures must be refined. Further work is required to make the Landsat inventory process both operational and competitive with existing systems.

During the period of 1976 through 1978, the Nationwide Forestry Application Program (NFAP) at NASA's Lyndon B. Johnson Space Center (JSC), extended ADP technology to intermediate-sized applications in ten ecosystems throughout the continental United States and Alaska.[6] The Ten Ecosystem Study was an ADP feasibility study using Landsat data, supporting aircraft imagery, and ancillary information for inventorying acreage of forest, grassland, and water. The same procedures were followed on each site and all image processing was done on a General Electric 100 interactive image processor. In summary, the overall accuracy of classification was about 80% ±5% (0.90 probability level). The consistency of classification, however, was not that good with a range of 35-95%. On sites with steep terrain, there were extensive areas of nonclassified data. Where brush was less than 50% of the cover, a pixel was classified as grass or bare ground depending on the amount of grass cover. Problems such as the latter will make it difficult to use Landsat data for rangeland inventories. When data from two dates were combined to take advantage of temporal information, classification accuracies were poorer than with either single date classification.

A good review of several forest and rangeland applications of satellite data in multistage and multiphase sampling designs is given by Rohde (1978b). Included are timber volume inventories, range inventory, inventory of wildland vegetation, inventory of rangeland converted to cropland, and inventory of strip mine disturbances.

Disturbance.—Attempts to classify and delineate areas of vegetation under stress met with mixed results. Rohde and Moore (1974) claimed they could delineate moderate and heavy defoliation caused by gypsy moths in Pennsylvania. Heller (1975) reported eucalyptus killed by a freeze in the Berkeley Hills area of the San Francisco Bay region in California could be detected on registered Landsat images for two dates (before and after). Weber et al. (1975) reported no success in detecting bark-beetle-killed trees in the Black Hills of South Dakota. However, heavy sulfur dioxide damage to

[6]Information furnished at the Ten Ecosystem final review, September 20, 1978, at JSC, NASA, Houston, Texas.

forest vegetation was detected and mapped by Murtha (1973) near Wawa, Ontario. Using photometric methods and ground estimates of defoliation from known sites, a map was produced for northeastern Pennsylvania indicating relative stress caused by gypsy moths (Talerico et al. 1977). From these results and still others, it seems entirely possible to map disturbances caused by unusual stress conditions occurring over broad areas. This is particularly true if multidate images and computer-assisted techniques are used to take benefit of spectral differences in first generation spectral data on computer-compatible tapes. However, unless one knows of the existence of stress conditions beforehand, or unless extremely sensitive and efficient techniques can be developed for multidate temporal data registration and analysis, there seems very little promise for Landsat data to systematically monitor the wildland resource base for vegetation stress.

Probably the greatest success in change detection using Landsat data will be realized when monitoring the vegetative cover for disturbances caused by disasters such as windstorm, flood, and fire or when monitoring human activities (Robinove 1975). For instance, acreages for clearcut and uncut mature timber determined from Landsat imagery were found to be reliable (Lee 1975, Lee et al. 1977). Using multidate imagery, burned-over areas and changes in the logged-over area were accurately isolated (Williams and Haver 1976). Aldrich (1975), comparing 1:63,360 scale photographic data and Landsat photographic data (1:1,000,000) detected 80% of all disturbances occurring over a 6-year period in one Georgia county. These included harvesting and silvicultural treatments, land clearing, regeneration, and others. In the Black Hills of South Dakota, Weber et al. (1975) easily detected the path of a tornado through ponderosa-pine-dominated forest land. From these studies it is concluded that to detect a change in the vegetative cover it must be 2 acres (0.8 ha) or larger in size and that the contrast with neighboring classes must be maximized by careful selection of temporal data for at least two dates.

In another stress-related application, rangeland might be monitored on temporal Landsat data using associated ancillary information during the spring and summer for (1) water quality and quantity; (2) location of high use areas, climatic patterns, and to establish base data for certain periods of a grazing season; and (3) environmental conditions to make yearly assessments of the changes within the rangeland environment (DeGloria et al. 1975). The information could be used to establish and document regular patterns of rangeland changes. Both conventional interpretation and computer-assisted techniques might be used to quantify changes in areal extent and/or onsite phenological changes in sensitive rangeland areas. However, current levels of accuracy in automated classification are not high enough and increased accuracy is needed in selecting proper Landsat dates, training sets, and the appropriate classification scheme.

Nonvegetative cover classification.—Surface water can be measured and monitored using both single-band IR (0.8-1.1 m) and multiband analysis. Both computer-assisted and conventional photointerpretation techniques have been effective (Klemas and Polis 1977, Ritchie et al. 1976). In fact, the National Aeronautics and Space Administration (1976c) developed a set of manual procedures, computer programs, and graphic devices designed for efficient production of precisely registered and formatted maps of water from digital Landsat MSS data.

Using computer-assisted techniques, Mausel et al. (1974) were able to identify and map all surface water bodies over 0.5 ha. In addition, they were able to identify five distinct classes of water and correlate them with several measures of water quality: (1) degree of silt in water, (2) depth of water, (3) presence of macro- and micro-biotic forms in the water, and (4) presence of various chemical concentrations in the water. In a study by Boland and Blackwell (1975), Landsat MSS data and the trophic status of lakes in the northeastern United States were used to develop predictors for two trophic indicators, to estimate lake position on a multivariate trophic scale, and to automatically classify lakes according to their trophic state. Their results using computer-assisted techniques indicated a potential for satellite data in lake surveys and for monitoring water-related activities. However, further refinements in the process are needed to make it an operational tool. In another hydrologic application, land use data derived from Landsat imagery improved significantly several streamflow characteristic equations in Delaware, Maryland, and Virginia (Pluhowski 1977).

Sampling schemes using Landsat data, aircraft observations, photographic measurements, and ground measurements can be useful in water inventory. Gilmer and Work (1977) used a 0.8% random transect sample and linear regression analysis of Landsat and aircraft observations of numbers of water bodies to estimate the adjusted number of water bodies in North Dakota. The estimates were within 3-8% (May and July imagery, respectively) of estimates made from low-flying aircraft. Information on lake numbers was necessary for managing migratory waterfowl. Thematic maps and statistics relating to open water were developed by Work (1976) using multiple-band techniques. However, he recommends a combination of single- and

multiple-band techniques to cut costs in operational applications of the procedures.

A stratified-random double-sample design was used to estimate water in three Virginia counties (Aldrich and Greentree 1977). Their technique used a combination of 1:125,000 BW photographic enlargements of Landsat bands 5 and 7, 1:120,000 scale color IR photographs, and ground checks to estimate water by type, size, accessibility, and utility classes. The cost was low, and the sampling error for the three-county area was less than 10%.

Nonvegetated soils in agricultural areas of the country can be accurately delineated and quantified by soil map unit composition using Landsat data and digital analysis procedures (Kirschner et al. 1977). However, mapping soils where vegetation covers the ground is particularly troublesome when using Landsat data. This is probably why there is a greater emphasis on aerial photography for soils mapping. Using Landsat photographic data as a background for soils mapping, however, greatly enhances information that can be deduced about hydrology and land use according to Westin and Frazee (1975). They also found that color composites were adequate for locating most boundaries between soilscapes. Regardless of soils type, it is interesting to note that soil moisture mapping over large areas can be carried out using satellite data if suitable weather conditions prevailed at the time of the imagery (Palabekiroglu 1977). This could be a very difficult requirement to satisfy in practice.

Special considerations.—There are many problems associated with the use of digital Landsat MSS data and the application of these data. These problems are usually associated in some way with cost, geometric fidelity of the data, effects of topographic relief, and the pixel by pixel registration of two or more Landsat scenes to make use of more than one data set. These problems are being pursued by researchers across the country; however, none of them has been satisfactorily resolved at this date with technology transferred to the user community.

The greatest cost of using Landsat data is not in the data itself but in the computer time required to perform the various routines involved. For instance, the cost of one set of tapes for a single scene covering about 6 million acres (2.43 million ha) is only $200. However, to have the data geometrically corrected to a map will cost in the neighborhood of $800-$1,000. This is before classification routines are used.[7] To reduce costs of processing Landsat data, computer programs must be efficient and use assembler language peculiar to the particular computer as much as possible.

[7]*Conversations with Roger M. Hoffer, Laboratory for Agricultural Remote Sensing (LARS), Purdue University, West Lafayette, Ind.*

One effective way of reducing computer costs is to use table look-up rules. These rules have made processing Landsat data by computer far more efficient (Shlien and Smith 1975). Table look-up schemes are based on a high correlation of the spectral intensities in the four MSS bands. This correlation reduces the number of distinct intensity vectors in an image to the order of several thousand compared with over 16 million possible vectors. The distinct vectors are stored together with the ground cover classification in the computer core memory. The accuracy of classification is comparable to classification by conventional methods but by an order of magnitude faster.

Computer programs for converting the coordinates of Landsat pixels to Universal Transverse Mercator (UTM) or geographic coordinate systems are readily available. Unfortunately, the most powerful programs with the best geometric correction algorithms require large computers with large storage capacities. The programs are usually written in a programming language which makes them unusable for most Fortran applications. Fortunately, the Image Processing Facility (IPF) at Goddard Space Flight Center, NASA, Greenbelt, Md., and the EDC have developed all-digital Landsat data processing systems that will be operational in late fall of 1979. The Goddard system will be capable of producing about 200 scenes per day as opposed to the present rate of 15 scenes per day. The IPF data will be provided to EDC on high-density digital tapes. EDC will make digital geometric and radiometric corrections to computer-compatible tapes as well as to all hard-copy imagery. This is a large step forward and will permit many more agencies to use Landsat data that could not previously because of the data quality and the need for greater geometric accuracy. Developments in Landsat digital enhancement at EDC should also improve the interpretation of Landsat images by manual technique (Rohde et al. 1978).

Boundary lines delineated by computer-assisted techniques using feature classifiers are often indistinct because pixels of mixed spectral data are misclassified. For example, when Landsat data were used to map land cover in Pennsylvania agricultural areas, many pixels overlapped small irregular field boundaries and caused difficulties in classification (Petersen and Wilson 1974). This problem is not uncommon and, in fact, could be called universal where land cover is heterogeneous in nature.

The boundary pixel problem is much like the "salt and pepper" problem of classification maps. Here, individual pixels of data classified different from surrounding pixels, sometimes erroneously as in the case of boundary pixels, detract from the classification map. This "salt and pepper" effect can be eliminated using an algorithm that refines the

computer classification of multispectral data (Kan 1975). The algorithm eliminates sets of data smaller than a prespecified size by merging them with the surrounding area. With 5- to 10-acre (2- to 4-ha) minimum mapping standards, this process would cause no problems with mapping accuracy.

Determining the final accuracy of a map produced by either manual or computer classification is always a problem. There are a number of techniques offered to solve this (Hord and Broomer 1976; Kan 1976a, 1976b; Genderen and Lock 1977). The Hord and Broomer technique calls for a random selection of plots for ground checking (with replacement) to meet the accuracy level desired. A table is provided from which the minimum number of correct sample points required to meet the accuracy desired is read for the lower 95% confidence limit. Whether or not the classification meets this requirement is determined; if not, then the accuracy actually achieved is determined. In a somewhat similar approach, Genderen and Lock (1977) have come up with a simple but reliable method for determining the sample size acceptable for valid statistical testing of land use map accuracy. Their method takes into account (1) the probabilities of attributing one land use to another, (2) the probability that the wrong class is erroneously included in any one class, (3) the proportion of all land mistakenly interpreted by the interpreter, and (4) the determination of whether errors are random or subject to a persistent bias. This is a much more appealing approach because it takes into account all types of error.

Kan (1976a) takes a different approach that is oriented more toward computer-assisted classification maps using Landsat data. He describes a procedure that takes the form of a theorem relating accuracy of all map classes to derived two-class map accuracies. A derived two-class map accuracy refers to the classification map (M-classes) when treated one class at a time versus the remaining classes. In another approach, Kan (1976b) evaluated the per-pixel Landsat classification accuracy of a map using a sample size which is small enough (2 by 2 pixels) to reflect pixel classifications but is large enough to absorb possible errors by misregistration and mixture pixels.

If spectral signatures for land cover are to be extended from one satellite image to another or from one location to another within a single image, corrections are usually required for differences caused by solar and atmospheric effects. This is somewhat analogous to sensitometric calibrations on color film to account for differences in solar and atmospheric conditions at the time of photography. The need for a technique to calibrate changes in solar and atmospheric effects has been well defined and documented by Dana (1978). In his research, he compared Landsat MSS data with terrain reflectance data measured from a low-flying aircraft using a four channel radiometer, an irradiance meter, and a video camera with recorder to provide support photography. His results showed that when the data were not adversely affected by soil moisture changes, a high correlation existed between Landsat radiance and terrain reflectance. A linear atmospheric model was developed by regression and is undergoing further testing.

Other investigators have developed empirical techniques for calibrating Landsat and photographic data for solar and atmospheric parameters to transform spacecraft radiance measurements to absolute target reflectance signatures (Rogers and Peacock 1973). A photometric technique that utilizes reflectances from scene shadow areas for calibrating remotely sensed data has been used extensively (Piech and Walker 1972, Talerico et al. 1977). Although the photometric technique is most appealing from an operational standpoint, it is difficult to learn details of the procedure. Its application to Landsat data with 80-m resolution seems inappropriate except in areas of steep terrain.

It is generally recognized that classification of multispectral data from a single time period alone may not be enough to permit sufficiently accurate classification and mapping of information from forest and rangeland. Spectral similarities of classes within a scene and spectral variability within a class, from one location to another and from time to time, may not permit adequate results. However, ancillary geographic data (including topography) and additional MSS data from other time periods may be used to improve classification and resulting resource information (Strahler et al. 1978). Topographic variables have a significant effect on Landsat signals and feature classifiers. The aspect of sloping terrain relative to the sun's azimuth is the major cause of variability (Cicone et al. 1977). Preliminary indications are that including topographic ancillary variables, stratifying on these variables, and developing training statistics within each stratum improves the performance of the feature classifier. However, more work is needed in this area to determine the full implication of these results.

Shadows in mountainous terrain caused by low sun angle at the time of Landsat passes create problems in feature classification. In most application demonstrations of Landsat data, these pixels are either left unclassified or they are classified like surrounding pixels. To reduce the effect of topographic shadow in Landsat data, Hart and Maxwell (1978) tested three transformations of Landsat data: (1) each spectral band value was divided by the average of all bands, (2) each spectral band value squared was divided by the average of all bands,

and (3) each spectral band value was divided by the square of the average of all bands. The normalization of single band reflectance (brightness) with the average of all bands was most effective for highly correlated original bands of data and least effective for inverse relationships on the red/IR response vegetation. They found that the accuracy of classification was higher for some between class distinctions based on subtle spectral difference detection but the accuracies were lower for class distinctions based on the magnitude of brightness. Accuracies were generally degraded by loss of brightness information.

The accuracy of multidate image registration is important for analyzing temporal data to improve cover classifications as well as to detect changes in the land cover. Detecting changes in the land cover as a result of land use and management practices will require selecting image dates that are compatible (seasonally) and geometrically corrected so that any pixel can be registered within a half a pixel of its contemporary on another image. The new process for geometrically correcting Landsat data tapes at EDS (National Aeronautics and Space Administration 1978) will provide temporal registration offsets between two Landsat images with the same World Reference Frame Numbers of <0.5 pixel. However, registration accuracy will depend to a great extent on the number of ground control points used, the accuracy of the maps on which coordinates are measured, and the accuracy of the coordinate measurements. Examples of some of the problems in change detection are reported by the Pacific Northwest Land Resource Inventory Demonstration Project (1978). They reported that multidate analysis of two Landsat images were overlayed and registered in a temporal analysis to detect land cover changes over a 3-year period. They used Laboratory for Agricultural Remote Sensing, Purdue University (LARSYS) and Image 100 (General Electric) systems in their data analysis to determine the location and extent of land cover changes. Classifying land cover for each date independently and then comparing the two for changes was unsatisfactory because most changes resulted from errors in classification. When a ratio of the two scenes was calculated and analyzed, it resulted in the detection of change but the method had only limited accuracy. The entire area of change detection including conventional photo interpretation, computer interactive interpretation, and automated interpretation will be investigated during the next few years.[8]

Although spectral data alone is used in most demonstrations of Landsat data applications, some people feel that spatial data should be given more attention (Sayn-Wittgenstein and Kalensky 1975). They say the reason why spatial data is not given much attention is that spectral data can be analyzed on a per pixel basis, whereas spatial data requires several to many pixels to obtain significant spatial patterns. They feel that, whereas spectral values are well known and easier to use, the analysis of spatial data is more difficult and requires a knowledge of complex mathematical approaches to define the spatial geometry of the data. Spatial data may be a requirement for many applications to obtain required classification accuracy in the future; however, its present use is extremely limited.

Thermal Scanner Data

The uses of thermal scanner data in classification and mapping generally fall into five categories: (1) fire detection and mapping, (2) vegetative stress detection, (3) land use and vegetative cover mapping, (4) ground water mapping and monitoring, and (5) geological structure classification. The use of thermal bands of data in MSS data analysis was covered in the section on Airborne Multispectral Scanners and will not be repeated here.

As brought out in the section on Airborne Multispectral Scanners, classification and mapping in the normal sense is rather difficult to do using thermal data alone. However, thermal data have been found useful to map thermal anomalies in the Yellowstone National Park. Producing a geothermal map uncovered a number of problems inherent in the thermal mapping process (Williams et al. 1976). Thermographs can be produced relatively free of geometric distortion if several provisions are made in the production of imagery. For instance, the line scan device must be stabilized about the three axes in the aircraft or the instrument motion around the axis must be recorded on tape with the video signal for stabilization of the imagery during film strip reproduction. In addition, the authors report that the average aircraft altitude above ground, the aircraft ground track, and the aircraft speed must be known to reproduce the data. Imagery must be rectified and the radiation response of the line-scan device must be constant.

Like geothermal anomalies, forest fires create targets of intense heat that are easily detected by thermal line scanners. An operational system utilizing two detectors sensitive in the 3- to 4-μm and 8.5- to 11.0-μm portions of the spectrum has been in use since 1971 (Hirsch et al. 1971). This system can detect targets as small as 0.09 m^2 at 600° C against backgrounds ranging from 0° to 50° C from

[8] *U.S. Department of Agriculture, Forest Service. 1978. Detecting and measuring changes in the renewable resource base using remote sensing techniques. A tripartite research and development study plan developed by the National Forestry Applications Program, NASA/JSC, Houston, Tex.; Special Mapping Center (Engineering Division), Reston, Va.; and the Resources Evaluation Techniques Program, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.*

altitude of 5,000 m. Polaroid prints are dropped to the fire boss with up-to-date fire information. The system can mark hot spots too small to print and provides information not available on one-detector units. The system is now operational for detection patrols, fire mapping for large fires, and mapping during mop-up operations on large fires. A smaller, lightweight IR line scanner is used as a fire spotter and can detect fires as small as 0.09 m^2 in size from 600 m above the terrain (Kruckeberg 1971).

Trees under the stress from bark beetle attacks have been shown in exhaustive field experiments to have temperatures higher than surrounding healthy trees (Weber 1971, Schmid 1976). Although temperature gradients as high as 7° C have been recorded, on the average the difference between infested and control trees is within 1° C. This small difference is usually masked by macroclimatic conditions that exist at the time of a thermal scanner pass. Although previsual detection of vegetation stress based on thermal differences is theoretically possible, detectors available today are not sensitive enough to overcome the prevailing weather conditions, closed cover, and winds that mask the warming effect of an infestation.

In summary, from what we know about thermal scanners there are possibly five mapping tasks for which thermal imagery will be useful: (1) geothermal hot spots under vegetation, (2) old stream channel locations, (3) high soil moisture, (4) thermal water pollution, and (5) spot fires and fire periphery.

Microwave Data

Of all remote sensing data, microwave is the least known and the least effective for wildland resource management uses today. This is probably because active (radar) and passive microwave systems are thoroughly understood by only a few people, the resolution of radar systems is comparatively poor, and other systems such as aerial photography and MSS's are easier to understand and use, and thus are more appealing. This has effectively limited applied research using active and passive systems.

Active Microwave

Because of its all-weather capability, side-looking, airborne radar (SLAR) is attractive for mapping in areas that are under nearly continuous cloud cover. Two such operational applications have been reported during the past 10 years. One application was in a portion of the Darien Province in the Republic of Panama (Crandall 1969). A portion of the Pan American Highway could not be completed because adequate map information was lacking. Using 5-foot corner reflectors at 13 locations as control points, radar imagery was produced and mosaics made to fill the information requirements. In 1970 Project Radam was organized to map more than 4.6 million km^2 in the Brazilian Amazon (Roessel and Godoy 1974). As a result, 160 semicontrolled SLAR mosaic sheets were released for public use. Each sheet covered 1° of latitude and 1.5° of longitude. For the first time, this vast area of rich resources was mapped for exploration. Results of the Panama and Brazil mapping projects indicate that radar mosaics can be made of the terrain using a minimum number of control points with fairly reasonable positional accuracy. Unfortunately, there is no evaluation of the informational content of these radar images for wildland resource management.

Several other researchers have made evaluations of radar imagery for wildland resource classification and mapping. For example, Bajzak (1976) in a test of radar imagery for forestry purposes, found that land formations could be clearly recognized on the radar imagery. However, the small scale of the imagery and interference inherent in the equipment limited the usefulness of the systems. Working with radar images with a ground resolution of 10 m and enlargements to 1:50,000, Francis (1976) found the images useful for surveying forest resources in the humid tropics. By adjusting the images to minimize reflections from vegetation, he was able to obtain an image of the underlying terrain. Drainage patterns, swamps, and flood plains, land under cultivation, mangrove forests, swamp forests, wet forest, dry forest, and general topographic features can be detected on the SLAR imagery for tropical forest surveys (Allen 1975).

According to Moraine and Simonett (1967), radar images contain subtle differences which the unaided or untutored eye at first sight cannot distinguish. To assist the interpreter, they developed a color-combining system to enhance the subtle distinctions and thereby expand the interpreters' detection and discriminatory abilities. Outputs of a data matrixing unit were presented to the three electron guns of a CRT in a color television set where they were combined in various colors to aid interpretation. Although image enhancement techniques have become commonplace in remote sensing, radar imagery still has not been accepted for general use because of problems in using the data.

There are a number of problems that exist when using radar imagery that must be understood and overcome. Not the least of these problems are proportionality geometrically in the near range, image layover causes areas of no detail fcr interpretation, shadowing with no interpretation data, and differences in range and azimuth scale. In areas

where slopes exceed 35% and 1,000 m in elevation, the usefulness of radar will be marginal unless careful consideration is given to both the geometry of the imaging system and the terrain itself (MacDonald and Waite 1971). Another problem is that magnification of radar imagery during interpretation is limited by the speckled effect in radar images of homogeneous scattering areas (Moore and Thomann 1971). In other words, the image falls apart. In a 15-m resolution system the limit of useful magnification is 10X. Thus, the small scale and limited resolution of radar imagery preclude interpretation of details. Enough detail is present, however, to categorize regions, and by sampling provide more detailed regional descriptions (Nunnally 1969).

Those applications where radar imagery will have its greatest potential are water, snow, or sea ice mapping; soil moisture mapping; drainage networks (McCoy 1969); landform mapping; combined physiographic and slope category maps (Nunnally 1969); and delineations of major geomorphic regions. Radar might have a role someday in preparation of small-scale regional or reconnaissance maps of vegetation types, delimiting vegetation zones that vary with elevation, tracing burn patterns from previous forest fires, determining the timber line, and identifying species by inference in areas characterized by monospecific stands (American Society of Photogrammetry 1975). Operationally, the U.S. Coast Guard uses radar to locate sources and map oil spills for purposes of prosecution. They also use radar for real time maps of ice conditions on the Great Lakes (Fischer et al. 1976).

Passive Microwave

Passive microwave is in its infancy and any applications are primarily developmental in nature. For instance, the USGS is studying the dielectric properties of soils, geological materials, snow, ice, and other materials conducive to layering experiments and soil moisture (Fischer et al. 1976). We need to learn more about the dielectric properties of vegetation, soils, and water before passive microwave systems can be evaluated for wildland resource applications.

INTERPRETIVE INFORMATION FOR SPECIFIC APPLICATIONS

Most interpretive applications of nonphotographic data relate to vegetative conditions including phenology, geology and unstable conditions, soils, and hydrology including soil moisture and water quality. As mentioned previously, most interpretive applications are also closely related to classification and mapping.

Vegetation condition.—To detect and flag trees or groups of trees in the forest that are infested with bark beetles or disease is a long-term goal in forestry. It is also a goal for states with high-value fruit tree crops. Although there have been attempts to detect green trees under attack by bark beetles (Weber and Polcyn 1972) and diseased trees infested with root rot (Weber and Wear 1970) the results have been negative. In citrus plantations there has been some success (89%) in identifying trees affected by the young tree decline using MSS data in the 0.82- to 0.88-μm band from an aircraft at 1,500 feet (Edwards et al. 1975). The MSS data indicated reflectance differences for trees identified as healthy on the ground which may be a clue to previsual detection. However, because some limited success has been achieved before in fruit plantations and forests, there does not seem to be much reason to believe that these results are any more conclusive.

Knowing the phenological schedule of range and forest land development could be helpful in some wildland management activities, planting programs, harvesting, grazing, insect control, and to a certain extent fire control. Activities are regulated by seasonal changes in vegetation. Image densities for Landsat band 5 (red wavelengths) and band 7 (near IR wavelengths) in the ratio (band 5 - band 7)/(band 5+ band 7) correlated well with forest vegetation changes (Ashley et al. 1975). The ratio is lowest with leaf-off and steadily increases with leaf development. These seasonal differences are also important in understanding growth and yield relationships (Ashley and Rea 1975).

Geology and unstable conditions.—Geologists around the world are finding that Landsat photographic data can be useful where no other data exist. One such example is in Turkey where bands 5 and 7 images were visually interpreted to prepare geologic, tectonic, and geomorphologic maps (Kayan and Klemas 1978). Band 7 was most valuable for identifying geologic formations, fault lines, and geomorphologic slope contrast. Band 5 supplemented band 7 by providing information on rock-soil boundaries, relationships between vegetation and structure, and vegetational tonal differences between steep slopes and subsurfaces.

Because it is necessary to interrelate various types of remotely sensed data, to integrate remotely sensed data with other sources of information, and to accommodate the wide dynamic range of electronic detectors (the dynamic range of Landsat detectors is estimated to be four times that which can be accommodated on film), there has been an emphasis in

recent years on research and development of computer-assisted processing and interpretation systems (Fischer et al. 1976). In reviewing progress in remote sensing, they found that Landsat will disclose large structural features on the earth's surface only visible on the uniform synoptic view of Landsat; geologic and geohydrologic features depending on the angle of illumination of snow, water, or vegetation distributions; distributions of some rock types, geochemicaanomalies, and alteration products; and surface water availability, surging glaciers, snow lines, and sedimentation.

Some characteristic features of rotational landslides have been identified on Landsat data. These characteristics are tonal mottling, tonal banding, major and secondary scarps, and ponds (Sauchyn and Trench 1978). The authors recommend 1:250,000 enlargements for regional analysis and 9- by 9-inch (23- by 23-cm) aerial photographic transparencies for detailed identification of landslides. Band 7 was most useful to accentuate ponds and shadows. They found that examination of both bands 5 and 7 was most suitable and under ideal conditions some landslides could be recognized. However, they do not recommend Landsat for detailed regional mapping where aircraft imagery is available. Landsat may be useful, however, for preliminary landslide recognition in relatively unknown areas.

In eastern Canada, Landsat imagery provided useful information to detect landslide hazards (Gagnon 1975). For example, bands 6 and 7 give good data on high ground water tables, high water content of surface material, and some buried valleys. Radar X-band real aperture (SLAR) did not add much information beyond that obtained by Landsat. However, thermal scanner imagery gives excellent results on surface water conditions, ground water level, seepage, infiltration, and saturation, but for best results the imagery must be combined with photography. Flows from water bodies and seepage are analyzed best through the study of temperature differences.

Not all geologic efforts have been successful, however. For example, Siegal and Abrams (1976) found that computer-aided supervised and unsupervised classification schemes, using computer-aided techniques, could not correctly classify rock formations (lithologic units) found in the field. They feel that this reflects the effect of inhomogeneity of geologic units and the similarity of their spectral signatures in the Landsat bands. Only 50% accuracy was achieved in classification.

Soils.—The amount of exposed soil and the degree and type of grass or other vegetative cover, which is a function of the seasons, have a strong relationship with Landsat spectral values. Landsat soil/grass four-band spectra at the end of the dry and grass dieback season are in reality the soil spectra (Levine 1975), and the Landsat four-band spectra for serpentine and sedimentary-derived soils are enough different from each other and the background to be classified by interactive unsupervised classification techniques. However, not all soil classification is this simple and, in fact, when the natural vegetation is heavy, it can significantly mask and alter the spectral response of the ground as measured by aircraft and satellite MSS (Siegal and Goetz 1977). Low albedo materials are significantly affected and may be altered beyond recognition by only a 10% green vegetative cover. As with Levine (1975), these authors found that dead and dry vegetation does not greatly alter the shape of the spectral response curve. The ratios of bands 4/6, 4/7, 5/6, and 5/7 are decreased by increasing amounts of vegetation. Tucker and Miller (1977) used regression analysis of soil spectral reflectance in the 0.35- to 0.80-m region to quantify maxima and minima for soil-green vegetation reflectance contrasts. This technique could be important to estimate the soil spectra reflectance and to quantify the wavelengths of maximum soil-green vegetation reflectance contrast.

Passive microwave usually receives very little attention in wildland resource applications. However, in one test on the west side of the San Joaquin Valley in California, Estes et al. (1977) found highly significant linear correlation between image tone density in the photographic output and moisture content in the top 5 cm of soil.

Hydrology.—A number of hydrologists have found that land use or thematic information from Landsat data are useful in hydrologic models (Dallum et al. 1975, Jackson et al. 1975, and Blanchard 1975). However, Blanchard and Baush (1978) found that spectral calibration of runoff curve numbers cannot be achieved on watersheds where significant areas of timber are within the drainage area. They found that wet surface conditions and vegetation grown throughout the year will prevent classifying runoff potential based on visible light only.

Monitoring the quality of water has become an important application of remote sensing and will gain greater use in the future. To detect senescent or dystrophic bodies of water, the presence and levels of chlorophyll "a" appears to be an important parameter. Chlorophyll "a" has been associated with eutrophication of water bodies which limits them for recreation, water supplies, and other purposes. Furthermore, low concentrations of chlorophyll "a" may be due to toxic substances from industrial wastes or other sources. A statistically significant linear relationship has been found

between aircraft-measured MSS data in the 0.44- to 0.49-μm, and the 0.70- to 0.74-μm spectral bands and chlorophyll "a" measurements for the same area in the James River in Virginia and New York's Bight ocean area (Johnson 1978).

To monitor oil spills, UV video systems have shown a great deal of promise although these systems are limited to daytime use under good weather conditions. There is a definite relationship between radiance of oil in the UV range and the type and thickness of oil (Wezernak and Polcyn 1971). Because of its "good day only" restriction, however, UV remote sensing is not likely to satisfy emergency situations. Microwave systems with all-weather capability have the greatest potential for responding to emergency situations. The U.S. Coast Guard has found a synthetic-aperture SLAR system provides the best results for detecting both natural and manmade oil slicks (Klaus et al. 1977).

Perhaps the greatest use of thermal imagery to date has been to relate gray scale values in the imagery to water temperatures, observe the source of the temperature gradient, and interpret the effect on the aquatic environment. Similar results can be obtained using calibration plates to accurately calibrate thermal IR scanner systems for water temperatures (Hoffer and Bartolucci 1972).

The best time of day or night for thermal imagery is related to the purpose of the mission. For example, nighttime thermal imagery is superior to daytime imagery in distinguishing rock types and map faults and fracture zones (Rowan et al. 1970) if acquired just before dawn. Generally speaking, however, tone signatures and image quality degradation in information content increases as night progresses. In daylight hours, equal amounts of reflected and thermal IR are returned to earth-oriented sensors operating between 3.0 and 4.5 μm. Therefore, an IR detector operating in this region may record phenomena related to reflected as well as reradiated energy (Estes 1974). For daytime operations, thermal scanning is confined to the 4.5- to 5.5-μm and the 8.5- to 13.5-μm regions. Exceptions to this are forest fires and volcanic activities (American Society of Photogrammetry 1975). Environmental conditions including clouds, heavy overcast, surface winds, time of day, and seasonal changes are sources of error in thermal imagery that are difficult to overcome and make the imagery difficult to use except under the most ideal conditions.

MEASUREMENTS OF RESOURCE PARAMETERS

Because nonphotographic data are nonstereoscopic by nature, only one- or two-dimensional measurements can be made. Measurements that are most successful are relative closure (percent of ground covered by the projection of vegetation foliage to the ground) and area. Because MSS and thermal scanner data are collected in pixels with ground coverage determined by the IFOV of the scanner, area measurements are based on the summary of all pixels adjusted for geometric errors classified in a particular category. The number of pixels in a category divided by the total in the mapped area, multiplied by the known total area, will result in the area in each category. Estimates such as these have been discussed under Nonphotographic Classification and Mapping. Generally speaking, the accuracies are about 80% ±5% at the 90% probability level.

Tree and stand measurements.—Attempts to relate spectral values from the four Landsat bands to timber volume and/or basal area have been unsuccessful. Successful use of Landsat MSS data in timber volume estimates were made by stratifying the population by type and condition classes with Landsat data and sampling within strata using aerial photography and ground plots (Titus et al. 1975, Harding and Scott 1978, Oregon State Department of Forestry 1978). In one instance it was found that Landsat data could not be used effectively to stratify forest land (Colwell and Titus 1976). In this example, the Sam Houston National Forest in Texas was found too homogeneous to provide meaningful strata.

Radar might have a role someday in discrimination of structural subtypes in cutover, burned, and regrowth forest; deriving estimates of vegetation density in sparsely vegetated areas; and supplementing high-altitude low-resolution photography in which texture differences related to vegetation are weakly expressed (American Society of Photogrammetry 1975).

Biomass measurements.—Measurements of species composition in the forest understory based on the overstory properties are not reliable (Sadowski and Malila 1977). Site is probably a much better basis for inferring understory density and composition, according to the authors. On the other hand, they say that understory biomass production potential would be better inferred on the basis of overstory density with improvements from the addition of site information. Although inferences about understory vegetation based on crown closure measured from MSS data and ancillary site information are a possibility, there is a great deal of research that must be done beforehand.

Following the Landsat-1 satellite launch in 1972 a great deal of effort was expended in developing relationships between the multispectral data and

forage production. In one experiment, Carneggie and DeGloria (1974) examined Landsat reflectance and irradiance data and demonstrated that (1) the time when germination occurred can be determined quantitatively from analysis of Landsat irradiance data, (2) the length of the green feed period can be determined and correlated with relative amount of forage produced in a given area, (3) Landsat reveals the location and extent of ranges affected by favorable or unfavorable climatic conditions that cause above and below normal forage conditions and production, and (4) Landsat data can provide a permanent record of range conditions at a given date and for a given year. Thus, Landsat seemed assured of a spot in the range managers' tool kit. However, there seems little of record to show that managers have used Landsat.

Many investigators have tried to quantify the forage production using computer-aided techniques. Some found that the red band (band 5) energy is strongly absorbed and the near IR band (bands 6 and 7) energy is somewhat more reflected by dense green vegetation (Deering et al. 1975). From this they hypothesized that a ratio of red to near IR should be an index of the greenness of a vegetative scene. This relationship also suggested that the difference between bands 7 and 5 normalized over the sum of these values can be used as a "vegetative index" or "band ratio parameters." Although this index holds up pretty well for very high biomass values, there is a threshold value or ground cover below which the estimate of biomass is unreliable. The capability of estimating green biomass has been demonstrated at 250 kg/ha increments in the 500-1,500 kg/ha range of productivity (National Aeronautics and Space Administration 1977). According to NASA, the normalized difference ratio of bands 5 and 6 was best for statistical determination of the amount and seasonal condition of rangeland vegetation in the Great Plains.

In another, somewhat related study, spectral reflectance measurements on sample plots in shortgrass prairie indicated that green biomass, chlorophyll concentrations, and leaf water content are directly interrelated to "functioning green biomass" (Tucker et al. 1975). Correlations between reflectance and these three measures were calculated at 91 wavelength intervals between 0.350 and 0.800 μm. Increasing amounts of dead vegetation during the season had little affect on the correlations. Tucker and Maxwell (1976) developed a linear relationship between integrated reflectance values (0.350-1.000 μm) and several canopy or plot variables (total wet biomass, total dry biomass, leaf water content, dry green biomass, dry brown biomass, and total chlorophyll content). Their purpose was to determine the relative statistical significance between integrated reflectance and the canopy variables for various wavelengths and bandwidths. Three spectral regions had strong statistical significance: 0.35-0.50 μm, 0.63-0.69 μm, and 0.74-1.00 μm in both the early and late growing season. There is greater spectral sensitivity early in the growing season between reflectance and grass canopy variables. Landsat bands 5 and 7 and RBV band 2 are well suited to biological remote sensing. Although more is being learned every day about quantifying the biomass from MSS data, there is nothing available at the present time to indicate that a breakthrough is imminent.

Other measurements.—Fuel moisture measurements may some day be monitored by satellite remote sensors. For example, there are indications that 1-hour time-lag fuel moisture estimates can be made over large forested areas with good results from synchronous meteorological satellites (SMS) (Waters 1975). However, the satellite data must be augmented with some estimates of humidity made from ground stations. The distribution of cloud cover can also be monitored and mapped from satellite data to indicate surface insulation. Some of the limitations of SMS-1 satellite data for fire danger applications are (1) in cloudy situations a surface view is almost impossible and only cloud cover information is available; (2) sensor resolution is large, so that surface information for smaller areas is lost; (3) cirrus and small uniform cloud types such as cummulus are underestimated; (4) earth location of the data is difficult by automated methods at the present time; and (5) it requires processing a great deal of data.

Snow and water area can be quantified quite readily on Landsat data. The quantification of areal extent of snow covering watersheds is a useful parameter in estimating snow water content for inclusion in water runoff prediction equations. Katibah (1975) developed an operational manual of interpretation techniques allowing for fast and accurate estimates of the areal extent of snow using Landsat enlargements. Using a combination of Landsat photographic image density slicing and radiance values from Landsat band 4, Thomas et al. (1978) measured areas of snowfields. They found that using absolute radiance values from computer-compatible tape data and consideration of the effect of topography on recorded snow reflectance were important. Using computer-assisted techniques to quantify snow cover can run into problems where cloud cover prevails. This will no longer be an issue with the advent of the "thematic mapper" on Landsat D which will include the middle IR portion of the EMS. Spectral differentiation between snow and clouds can be achieved in the middle IR portion of the spectrum (Hoffer et al. 1975). Water inventory can be accomplished equally as well by either man-

ual or computer-assisted techniques (Aldrich and Greentree 1977, National Aeronautics and Space Administration 1976c).

OBSERVATIONS AND COUNTS OF OCCURRENCES

There are very few potential applications of non-photographic remote sensing to make observations. The observation of water pollution has been discussed previously and will not be repeated. In a study in New England, Simpson (1970b) compared the capabilities of radar, thermal IR, and BW photographs to provide data on location, size, and slope of builtup areas. He concluded that only under special operating conditions relating to weather, cost, and similar factors would one select radar or thermal IR in preference to photography.

Parker and Driscoll (1972) made a study of the application of thermal IR to big game animal counts. They flew an IR detector (0.8-13.0 μm) with a 2.5 mrad IFOV over pens containing 66 deer and antelope. They found that the temperature difference between animals and their background was enough to permit detection from either 300 or 500 feet (91.5 or 152.4 m). However, at a safer flying altitude of 1,000 feet (305 m), detection was not possible. This was primarily the result of the 2.5-m ground resolution of the scanner at that altitude.

Because animals are effectively insulated, their surface temperatures are usually considerably lower than their internal temperatures (Parker 1971). Furthermore, the surface temperature of an animal at any time depends on a number of environmental factors—the air temperature, solar radiation, atmospheric water vapor pressure, and windspeed. Parker and Harlan (1972) found that missions for deer detection by airborne thermal IR scanner should be flown during periods of no direct-beam solar radiation (i.e., sunset to dawn). This would maximize the temperature difference between the deer and its background. However, further investigations in basic thermal IR methods are recommended to resolve variations (Parker and Driscoll 1972).

COSTS

This paper has reviewed many state-of-the-art, wildland applications of remote sensing technology. From the review it is apparent that not every sensor is equally effective or efficient for every job. In fact, it would be difficult to recommend a universally used remote sensing system, a standard film scale, or season of the year for every USDA Forest Service user need. Instead, each requirement for remotely sensed data should be judged by itself and with others to select sensor parameters that will provide the most effective use of remotely sensed data in resource management activities. The more uses for a particular set of data, the more cost-effective that data will be. However, the original purpose of the data should never be compromised.

DATA COLLECTION

Data collection costs include all expenses involved in delivering the remotely sensed data product to the user. Included are costs of the aircraft, crew, film, photographic laboratory, and other internal costs peculiar to the aerial contractor. Parameters that will vary and affect the costs of aerial photography are swath width, aircraft utilization (hours/year), flight efficiency (percent), flight cost (dollars per hour), data cost (dollars per image), and the number of duplicate images to be delivered (Arno 1977). Because of these variables, the cost of remote sensing data collection is very difficult to determine except on a mission by mission basis.

As a general rule, the costs of aerial photography will decrease approximately 5% each time the photographic scale is halved (Ulliman 1975). For example, decreasing the scale from 1:20,000 to 1:40,000 will decrease the number of photographs by a factor of four (e.g., the number of photographs is reduced from 56 to 14 for every 100,000 acres (40.486 ha) of coverage (table 4)). Film and processing costs will also be reduced four times. Aircraft and flight crew costs, however, will decrease only 2.3 times (Stellingwerf 1969). This is probably because unproductive cross-country flight time is the same regardless of scale. Costs internal to the company (including overhead), in one instance at least, is about 70% of the total regardless of scale (Ulliman 1975). Thus, greater percentage savings in flying and photographic costs are masked by the high internal company costs and result in only a 5% reduction in the cost of aerial photography each time the scale reciprocal is doubled.

According to Arno (1977), the total cost of USDA medium-scale photography in 1973 was $891,000 or $4 per square nautical mile ($1.17 per km^2). He continues to say that, depending on scale, film type, altitude, focal length, and other factors, the cost of medium-scale USDA photography since 1964 varied from $2 to over $13 per square nautical mile ($0.58 to $3.79 per km^2). For comparison, he describes a typical cost for a more or less typical high-altitude system including a Learjet, a 6-inch (152-mm) focal length lens on a 9- by 9-inch (3.54- by 3.54-cm) film, a flight efficiency of 40%, a utilization rate of 1,000 hours per year, a swath width of 12

Table 4.—Photographic scale coverage for estimating photo requirements per 100,000 acres

Photo scale	Number acres per square inch	Number acres per photo[1] (3.6 by 7.65 inches)	Number photos per 100,000 acres
1:15,840	40	1,101	91
1:20,000	64	1,763	57
1:24,000	92	2,534	39
1:30,000	143	3,938	25
1:40,000	255	7,023	14
1:60,000	574	15,808	6
1:120,000	2,296	63,232	3

[1]60% overlap; 15% sidelap.

nautical miles (22.2 km) (1:100,000 scale), and one duplicate film copy to the user at $0.27 per square nautical mile ($0.08 per km²). Of course, changes in any of the parameters will have a great influence on the cost per unit area. If internal company costs (Ulliman 1975) are added to this typical cost, the total for 1:100,000 scale photography would be nearly $1 per square nautical mile ($0.29 per km²) or one-fourth the average cost of USDA photography in 1973.

High-altitude panoramic cameras have been used in demonstrations for wide-area dead timber and forest damage assessments in recent years. Although the concept is appealing and the resolution (0.2-1.5 m) is required for some user needs, these systems should not be used where lower resolution systems (2-5 m) will perform adequately. A 24-inch (610-mm) focal length panoramic photography system has been found to exceed the data acquisition costs of a lower resolution 6-inch (152-mm) focal length system by 39% (Arno 1977). The higher costs are generally associated with larger amounts of data and higher data processing costs.

There are very few direct references to the data acquisition costs of optical-mechanical scanners or microwave systems. However, much of the aircraft flight costs involved with aerial photography for comparable swath widths should be applicable to scanners as well. Generally, scanners require a great deal of data to be generated and processed if any substantial area is to be viewed with good resolution. For example, where 3-m ground resolutions are required, substantially greater aircraft and data processing costs are encountered with scanners than by film systems (Arno 1977). This is because imaging swath widths are greatly reduced if resolutions are to be comparable to the photographic systems.

DATA PROCESSING

Data processing in the sense used here includes preparations for and the analysis of remotely sensed data to produce resource statistics and/or maps. Both conventional photointerpretation and computer-assisted techniques are included. Any comparative cost analysis of these techniques for wildland resource management purposes should ideally be done for the same area by collateral research efforts. Unfortunately, this is seldom possible or practical. The best one can expect is a cost analysis with each remote sensing application study. However, this too is sometimes difficult to provide with operationally realistic data.

Very often we are inclined to accept new technology as best and most cost effective because new data is collected of a type and frequency of coverage previously impossible. This is particularly true if the technology is new and sophisticated (Craib 1977). However, this new technology often can do only part of a given job. Because the entire job must still be done, older, more conventional techniques must be used at least in part which add to the total cost. Sometimes the most cost-effective procedure to complete a job is the older less-sophisticated conventional technique.

Conventional photointerpretation of aerial photographs has been compared with satellite data for delineating soils types and vegetation (Eastwood et al. 1977). In their comparison of production costs for a map of soils types, slopes, and erosion areas, the authors used low-altitude BW photographs. They found that photo production costs including field checks, editing and compiling the maps was $166 per km². The map accuracy was 99%. The same map made from satellite data using computer techniques was $61 per km². An accuracy of 90% was achieved from the satellite data. Vegetation maps were made using low- and medium-altitude BW, CIR, and color films. The cost comparison for 1:250,000 and 1:24,000 scale maps was $3.35 per km² and $29.63 per km², respectively. The mapping accuracy was 95%. The same vegetation map was produced using satellite data for only $0.95 per km² on a 1:250,000 scale map base. From these comparisons, it can be said that the cost advantage was about three times

for the satellite method of soils and vegetation mapping, but the map accuracy dropped 10-15%.

Stellingwerf (1969) reports that using aerial photography will show a reduction in interpretation cost of four times for each doubling of the scale reciprocal. However, this seems rather high based on experience. Although the number of pictures to interpret, and consequently the photo preparation, handling, and set up costs are reduced four times, the interpreter must cover the same ground area in classification and mapping with somewhat less image detail to interpret. Thus, total interpretation costs probably are not reduced more than 25% for each doubling of the scale reciprocal. The cost of classifying and mapping land-use and forest cover types on 1:120,000 scale CIR has been estimated to be $0.006 per acre ($0.015 per ha) (Aldrich et al. 1976).

Computer-aided classification entails a number of distinct routines or procedural steps to correct the multispectral data radiometrically and geometrically and to calibrate the data for system errors. Depending on the efficiency of computer software programs, the efficiency of the machine-operator interface, the amount of ground calibration, number of classifications, the effectiveness of the classification procedures, and the products delivered, costs can vary widely. The Oregon State Department of Forestry (1978) forest inventory for Douglas County using Landsat MSS data cost $0.0070 per acre ($0.017 per ha). This cost was compared with the $0.018 per acre ($0.045 per ha) for a recent forest survey using conventional techniques; however, the inventory products were different. Classification maps at two scales, areas, and forest volume statistics were produced by the Landsat-based inventory. A San Juan National Forest inventory using Landsat MSS data and aerial photographs resulted in a cost of $0.0156 per acre ($0.0385 per ha) but essentially only one classification map scale and area statistics were provided (Krebs and Hoffer 1976). In the Washington forest productivity study, Harding and Scott (1978) reported a cost of $0.026 per acre ($0.064 per ha) for a Landsat-based inventory of forest resources by age and basal area classes by ownership class. A comparable inventory using ground plots and photointerpretation cost $0.04 per acre ($0.10 per ha). The Forestry Applications Program (USDA Forest Service/NASA) has reported costs of $0.03 to $0.06 per acre ($0.15 per ha) for mapping forest and forest-related resources to level II categories given in USGS Professional Paper 964 (Anderson et al. 1976).

In summary, computer-aided data classification and processing costs will vary depending on the procedure used and the data products delivered. In general, these techniques will cost $0.02-$0.07 per acre ($0.05-$0.17 per ha). The accuracies of the data products are somewhat lower than those produced by conventional procedures.

FUTURE PLANS AND GOALS

Although the USDA Forest Service recently defined its remote sensing user requirements, specific goals were not identified or responsibility assigned. With the mechanical capabilities of remote sensing advancing rapidly during the past decade and prospects for greater advancements in the future, there is a need for increasing the biological capabilities of remote sensing technology. This means defining specific goals and responsibilities for future developments.

Some of the expected advancements in satellite data collection capabilities, agency goals and recommendations, and specific remote sensing research and development needs are discussed in the next sections.

ADVANCING SATELLITE TECHNOLOGY

Technological advances in satellite-acquired, remotely sensed data look promising for the next decade (Doyle 1978). As the leader in remote sensing from earth orbiting satellites, NASA has several satellite packages either scheduled or recommended for the late 1970's and early 1980's. Landsat-3, SeaSat-A, and the HCMM satellites were launched in 1978. These satellites have been referred to elsewhere in this review.

NASA has approval to launch Landsat-D in 1981. It is proposed that Landsat-D carry a four-channel MSS and a "thematic mapper" scanner. The "thematic mapper" will gather data with a seven-band MSS from an altitude of 705 km. In addition to six bands in the visible and reflected IR regions of the EMS, one thermal IR band will be included. The ground resolution of the "thematic mapper" will be 30 m. Of some concern to the user community is the 7- to 8-day delay between data collection in adjacent swaths. This may complicate future signature development and correlations between adjacent swaths. There is also some concern among Landsat users that unless a Landsat four-band MSS is included with the "thematic mapper," the continuity of Landsat type data will be lost when Landsat-2 and Landsat-3 are no longer operational. This could be a serious problem if forest and rangeland uses of Landsat data are operational by 1981.

The space shuttle, with possibly as many as five vehicles, will carry out 30-50 missions each year. This orbital vehicle can be recovered and reused

after each mission. It is anticipated that the space shuttle will be the primary space transport system for the next 2 decades. The first orbital flight test to carry an instrumented pallet will be launched in 1980. Five experiments are scheduled in air pollution, ocean bioproductivity, lightning storms, radar all-weather surface observation, and multispectral radiometry. One flight scheduled for 1981 will reach as far north as 57° north latitude with a large format camera for near vertical photography.

There are several additional satellites scheduled in the 1980's that will have less impact on renewable resource programs. However, the reader is referred to Doyle (1978) for more information regarding these and other satellites discussed in this review.

It is likely that high-altitude photography will be flown over the United States beginning in 1979 or 1980. A joint effort by 11 federal departments and independent agencies would provide funding for 1:80,000 high-definition BW and 1:60,000 CIR aerial photography. The USGS is the lead agency. BW films would be stored and referenced at the EDC. CIR would be stored and reproduced at the Agricultural Stabilization and Conservation Service (ASCS) Photographic Field Office in Salt Lake City, Utah.

AGENCY PROGRAMS

In 1967 a program of research for remote sensing was prepared for the USDA outlining the status of remote sensing, applications, potential benefits, and research to meet future needs.[9] Seven wildland applications for which remote sensing had potential benefits were identified: (1) range surveys to aid in assessing carrying capacity, (2) soil mapping, (3) watershed inventory and planning, (4) forest inventory, (5) forest insect and disease detection, (6) detection and mapping of forest fires, and (7) detection of forest fire hazard levels. An 11-point research program was presented that would lead to the realization of these benefits. Without assigned responsibilities, however, it is difficult to determine the current status of these 11 research areas without searching the literature as was done in this review.

In 1974 the National Academy of Sciences (1974) appointed a committee to review the progress of remote sensing in resource and environmental surveys and make recommendations for research and development. They identified three applications with the greatest probability of success for a satellite system from both the standpoint of technical feasibility and potential value: (1) inventory and monitoring of rangelands conditions, (2) inventory and monitoring of forests and forest conditions, and (3) habitat inventories for use in wildlife management.

The committee report is optimistic for Landsat-type data use in operational wildland resource management. However, the report states that a Landsat-type system cannot meet all forest and rangeland inventory and monitoring needs. The committee believes that Landsat data could provide the first level of data in the design of a cost-effective multistage inventory system for greatly improving present renewable resource assessments. They called for an improvement in spatial resolution of satellite data to 10 m to allow better identification of vegetative species composition. They also concluded that broad-area coverage provided by Landsat should lead to improved wildlife habitat inventory procedures particularly in mountainous regions. Here, Landsat coverage supplemented by more detailed photographic data for sample areas is expected to provide cheaper and more effective controls for regional habitat evaluations. The committee recommends changes in future satellite MSS's to include data channels in the blue and blue-green spectral regions and additional reflective IR and thermal IR channels. However, they made very few recommendations for future work in applications other than the development of yield prediction models incorporating Landsat and meteorological satellite data. They also recommended that earth resources data processing be converted to all-digital techniques and that the primary archival medium be digital storage.

NASA has identified and defined a number of objectives for the civil space program over a 25-year period (National Aeronautics and Space Administration 1976d). Two objectives are related to National Academy of Science (1974) and USDA[8] recommendations: (1) to reach a capability to inventory the timber of the nation's forests on a 5-year cycle with yearly updates based on multistage sampling techniques, and (2) to provide timely assessments of range conditions to support efficient cattle management in the West.

NASA recognizes that multistage sampling techniques and techniques for handling species mixes must be optimized and demonstrated before operational capability can be attained. Once this has been accomplished for broad-area timber inventories, the techniques will be extended to high-resolution data to achieve required accuracies for specific area (inplace) timber inventory systems.

According to NASA, assessments of range conditions will be implemented by a range condition status center by 1982. To accomplish this, NASA has set out to develop empirical vegetation models, agromet yield models for range vegetation, and

[9]*A national program of research for remote sensing prepared by a task force of the U.S. Department of Agriculture and the state universities and land grant colleges, 1967.*

optimization of vegetation models to use with high resolution data.

A USDA working group in 1977 defined major departmental information requirements that could be potentially supported by application of aerospace technology.[10] These information requirements are (1) early warning of changes affecting production and quality of renewable resources, (2) commodity production forecast, (3) land use classification and measurement, (4) renewable resource inventory and assessment, (5) land productivity estimates, (6) conservation practices assessment, and (7) pollution detection and impact evaluation.

The first four information requirements have the greatest priority in project planning in the future. All seven requirements are now included in the "Secretary's Initiative" for remote sensing.[11]

CONTINUING RESEARCH AND DEVELOPMENT GOALS

By integrating the limitations of remote sensing as pointed out in this review with recommendations and goals of the National Academy of Sciences (1974), USDA's Remote Sensing Task Force,[9] NASA's 25-year plan (National Aeronautics and Space Administration 1976d), and USDA's information requirements[10] several areas of continuing research can be identified:

Early warning of changes affecting production and quality of renewable resources.—There should be a continued effort to determine whether trees attacked by bark beetles or disease can be detected previsually by airborne MSS, thermal, and microwave sensors based on their changing reflective characteristics, temperature, or dielectric properties.

Developments for registering digital data for two or more Landsat scenes to point out changes in the forest area base, changes in the forest environment caused by man or natural phenomena, and changes in range productivity should be continued. Additional research is needed to learn how to improve the selection of temporal data for change detection and how to integrate change information into a data base management system.

For national, regional, and state renewable resource inventories, there is a need to develop methods that overlay digital Landsat data with precise permanent sample locations. This would have applications in all resource assessments to update inventories for change.

Manual and computer-aided manual methods of change detection should be developed for use with Landsat photographic data products and image enhancement devices.

Land-use classification and measurement.—Determine ground cover classes (vegetation, soil, water, and other) and other conditions inherently separable within remote sensing spectral data (digital) to aid in land-use classification. Emphasis should be on separating wildland categories from developed land—agriculture, urban, etc.

Improve classification algorithms to account for within class variation, atmospheric and solar interference, topographic relief, and shadows.

Continue efforts to use digitized small-scale and very small-scale aerial photographs for land-use mapping with emphasis on separating wildlands from developed lands. Both spectral values (density) and spatial distributions should be investigated for wildland vegetation cover and condition classification.

Develop accurate methods for overlaying digital (Landsat or photographic) data with political or administrative boundaries for mapping and statistical data summaries.

Develop improved methods to determine optimum exposure of aerial films and film density calibration techniques. Exposure differences within and between photographs caused by differences in illumination, atmospheric and solar interference, and camera characteristics must be corrected to use digitized photographic data.

Continue efforts to develop spectral signature extension capabilities to use in land classification by computer-assisted techniques. These efforts should include development of improved methods for incorporating digital terrain data.

Renewable resource inventory and assessment.—There should be a continuing effort to integrate developments outlined under information requirements above in operational resource inventory.

Development of yield prediction models for range vegetation using both low- and high-resolution data should have a high priority. However, since NASA is pursuing this development, the USDA Forest Service should monitor developments closely and transfer technology when available.

Renewable natural resource inventories will rely on conventional medium- and small-scale aerial photographs for many years. Therefore, research to integrate Landsat digital data and conventional photography in multistage or multiphase sampling

[10] *Memorandum with enclosures from H. L. Strickland, USDA Remote Sensing Coordinator, to USDA remote sensing contacts dated November 18, 1977.*

[11] *U.S. Department of Agriculture. Secretary's Initiative, Joint Program of Research and Development of Uses of Aerospace Technology for Agriculture Programs, March 8, 1978.*

designs should continue. Resource parameters measured at ground and several levels of aerial photography should be investigated to develop correlations with Landsat spectral values.

Special purpose photographic acquisition systems developed by Department of Defense, NASA, and other government agencies should be investigated for their natural resource capabilities. One example is the KA-80-A optical bar camera which with its wide-area coverage and high-resolution capabilities was found useful for statewide forest insect impact assessment. The cost and overall effectiveness of this system should be weighed against the cost and effectiveness of conventional large-format cameras.

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APPENDIX A

Glossary of Terms

ADP: Automatic data processing.

Algorithm: In computing, a statement of the steps to be followed in the solution of a problem. In remote sensing, usually refers to a procedure, mathematical or otherwise, for correcting and/or classifying digital data.

Aperture: The opening in a camera lens diaphragm (field of view) through which light passes. In thermal and multispectral scanners, the entrance slit through which reflected energy is transmitted to the detectors.

Array: An ordered set of something (e.g., Landsat multispectral scanner detectors are arranged in side-by-side arrays of six detectors for each of the four multispectral bands).

ASCS: Agricultural Stabilization and Conservation Service, U.S. Department of Agriculture.

Atmospheric interference: A reduction and/or distortion of reflectance measurements made from above or from within the atmosphere, caused by moisture and particles of matter in the atmosphere.

Atmospheric luminance: The intensity and quality of light reflected from the atmosphere.

Atmospheric transmittance: The quality of the atmosphere that allows light (solar) energy to be transmitted to the Earth's surface.

Backscatter: The scattering of radiant energy into the hemisphere of space bounded by a plane normal to the direction of the incident radiation and lying on the same side as the incident ray. In radar usage, backscatter refers to the radiation reflected back toward the source.[1]

Band: A group of adjacent wavelengths of the electromagnetic spectrum sensed by a multispectral scanner or passed by a band-pass filter and recorded on photographic film.

Band-pass filter: An optical filter that allows only defined portions of the electromagnetic spectrum to pass to the sensor surface.

Bicolor film: Photographic film with two color sensitive layers.

Biomass: The total quantity of living organisms of one or more species per unit of space, or of all the species in a biotic community.[2]

[1]*American Society of Photogrammetry. 1975. Manual of remote sensing. Robert G. Reeves, ed. American Society of Photogrammetry, Falls Church, Va. p. 2,061-2,110.*

[2]*Hanson, H. C. 1962. Dictionary of ecology. Philosophical Library New York, N.Y., 382 p.*

BW: Black and white. Used as an acronym for panchromatic films and black and white printing materials.

CIR: Color infrared. A false color film sensitive to reflected infrared radiation but not sensitive to thermal infrared radiation.

Contrast: Ratio of the energy reflected from two objects. Sufficient contrast permits distinguishing between those two objects on remotely sensed data.

Crown closure: Percent of ground area covered when the periphery of all tree and/or plant crowns are projected vertically to the ground. Sometimes called canopy cover.

CRT: Cathode ray tube.

Data set: A defined set of data (e.g., digital multispectral data for a defined area).

Detector: A device providing an electrical output that is a useful measure of incident radiation.

Dielectric properties: The properties of a material or object that allow it to conduct an electrical current.

Discriminant: A mathematical expression providing a criterion for the behavior of another usually more complicated expression, relation, or set of relations.

DMA: Defense Mapping Agency, U.S. Department of Defense.

EDC: The EROS Data Center, Sioux Falls, S. Dak.

EMS: Electromagnetic spectrum. An ordered array of known electromagnetic radiation including cosmic rays, gamma rays, x-rays, ultraviolet, visible light, infrared radiation, and microwaves.

EREP: Earth Resources Experimental Package (Skylab), National Aeronautics and Space Administration.

EROS: Earth Resources Observation Systems, Geological Survey, U.S. Department of Interior.

Focal length: The distance measured along the optical axis of a lens from the optical center (rear nodal point) to the plane of critical focus of a very distant object.[1]

Geomorphic: Of or pertaining to land forms and surface features of the earth.

Ground resolution: The size of the smallest detectable or measurable detail on remotely sensed imagery.

HCMM: Heat Capacity Mapping Mission.

IFOV: Instantaneous field of view. The field of view (aperture) designed into scanning radiometer systems (thermal scanners and multispectral scanners) so that while the radiometer is scanning an arc of about 120°, only the small area in the field of view is recorded in any instant.

Illuminance: Illumination or the lighting up of a scene. In physics, the luminous flux per unit area on an intercepting surface at any given point.

Imaging sensors: Sensors which give a visual representation of electromagnetic energy from all objects within their field of view. Included are cameras and film, multispectral scanners, thermal scanners, radar and passive microwave, and video systems.

IPF: Image Processing Facility, Goddard Space Flight Center, National Aeronautics and Space Administration, Greenbelt, Md.

IR: Infrared. Sometimes used as an acronym for black and white films that are sensitive to reflected infrared radiation.

Irradiance: The amount of light received from a distant source and measured on a surface. In physics, the radiant flux density on a given surface. Usually expressed in watts per square meter.

JSC: Lyndon B. Johnson Space Center, National Aeronautics and Space Administration, Houston, Tex.

LACIE: Large Area Crop Inventory and Evaluation. A joint project of United States Department of Agriculture, National Aeronautics and Space Administration, and National Oceanic and Atmospheric Administration.

Landsat: Originally known as the Earth Resources Technology Satellite. A research and development tool to demonstrate that remote sensing from space is a feasible and practical approach to efficient management of Earth's resources. Landsat satellites contain two sensor systems: a return beam vidicon subsystem and a four-band multispectral scanner subsystem. Landsat-3 has a five-beam multispectral scanner that includes one thermal infrared band.

Landsat-1: Originally ERTS-1, was launched in June 1972 and ceased to function in January 1978.

Landsat-2: Launched in January 1975 and is still functioning.

Landsat-3: Launched in January 1978 and is still functioning. The thermal band failed in July 1978.

Landsat MSS: A four band optical-mechanical multispectral scanner. Band 4 = 0.5-0.6 μm (green), band 5 = 0.6-0.7 μm (red), band 6 = 0.7-0.8 μm (IR), and band 7 = 0.8-1.1 μm (IR).

LARS: Laboratory for Agricultural Remote Sensing.

Microdensitometry: The measurement of film density using transmitted light from a calibrated light source in units as small as 1 μm. Film densities are recorded on magnetic tape or paper charts for computer or visual analysis.

Microwave: Very short electromagnetic energy between 1 mm and 1 m in wavelength. Bounded on one side by the far infrared and on the other by very high frequency radio waves.

mrad: Milliradian. The angle at the center of a circle subtended by an arc equal in length to one-thousandth the radius.

MSS: Multispectral scanner (see optical-mechanical scanner and Landsat multispectral scanner).

Multiband: Simultaneously observed targets on several filtered bands. Usually applied to photography where two or more cameras are used to photograph targets on infrared or panchromatic film using band pass filters.

NASA: National Aeronautics and Space Administration.

NFAP: National Forestry Application Program, Forest Service, U.S. Department of Agriculture, and the National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, Tex.

NOAA: National Oceanic and Atmospheric Administration.

Nonimaging sensors: Sensors which give quantitative measures of the integrated intensity of electromagnetic energy from all objects within their field of view. Included are radiometers and spectrometers.

Optical-mechanical scanner: An airborne-or satellite-borne system incorporating both an optical and a mechanical system to scan the Earth's surface. Variations in scenic brightness are translated into electrical signals which can be amplified to produce a graphic image in one or more bands of the elctromagnetic spectrum. Both thermal and multispectral scanners fall in this category.

PDS: Photometric Data Systems.

Photographic set: A set of aerial photographs covering a defined area.

Photometric: Of or pertaining to measurement of the intensity of light.

Photon: The elementary quantity or quantum of radiant energy.

Pixels: Single picture elements of digital image data recorded on magnetic tape using a microdensitometer, thermal scanner, or multispectral scanner.

Platform: The vehicle or station from which remote sensing is carried out. These include towers, low altitude aircraft, high altitude aircraft, and satellites.

Polarization: The direction of the electric vector in an electromagnetic wave (light or radio).[1]

Previsual: Detectable before it is visible to the human eye or by remote sensing in the visible portion of the electromagnetic spectrum. Plants under water stress are to some degree characterized by a breakdown in leaf structure which may affect reflectance in the infrared portion of the electromagnetic spectrum.

Radiance: The brightness of an object as seen from a remote observation point (reflectance). In physics, it is a measure of the power radiating from a unit area of a source through a unit solid angle. Typical units of radiance are watts per square meter ≥ steradian.

Radiation: The emission and propagation of energy through space or through a material medium in the form of waves.

RBV: Return-beam vidicon. A modified vidicon television camera tube in which the output signal is derived from the depleted electron beam reflected from the tube target.[1]

Resolution element: In Landsat data, one pixel or 57 by 79 m on the ground.

Resolve: To separate one image object (bar target) from another for either detection or measurement purposes.

Resolving power: The changes in resolution in an image that depend on film, relative lens aperture, lens aberations, and the angular distance of the object from the optical axis of the system.

Scale: The ratio of a distance on a photograph or map to its corresponding distance on the ground. Usually expressed as a representative fraction.

Secondary scarp: An escarpment, cliff, or steep slope formed of eroded or disintegrated rock of some extent along the margin of a plateau, mesa, terrace, or bench.[3]

Shadowing: Obstructing of a radar beam by an object elevated above its surroundings preventing illumination of the area behind it.

Signal polarization: (see polarization).

[3]*Adapted from Glossary of Geology and Related Sciences. J. J. Howell, Coordinating Chairman. American Geological Institute, 2101 Constitution Avenue, NW., Washington, D.C.*

Signature: Any characteristic or series of characteristics by which an object or ground cover is recognized. Usually used in the sense of spectral signature, as in Landsat multispectral scanner data or photographic data.

SLAR: Side-looking airborne radar.

SMS: Synchronous meteorological satellites.

Solar altitude: The altitude of the sun in degrees above the horizon. Varies with time of day, time of year, and geographic position on the earth.

Solar angle: The angle made by the intersection of the sun's azimuth and a line through true north. The angle will vary with time of day, time of year, and geographic position on the earth's surface.

Space shuttle: A reusable earth orbiting space workshop which may be launched in 1981.

Spectral distribution: The portion of the electromagnetic spectrum represented in a pictorial scene and displayed in remotely sensed data.

Spectral resolution: The finest separation that can be made between image details based on spectral data alone.

Spectral sensitivity: The wavelength or frequency of a portion of the electromagnetic spectrum which a given sensor is designed to measure.

Spectrometer: A device to measure the spectral distribution of electromagnetic radiation.

Tricolor film: Photographic film with three color-sensitive layers.

USDA: U.S. Department of Agriculture.

USGS: U.S. Geological Survey..

UTM: The Universal Transverse Mercator map projection system.

UV: Ultraviolet. Radiation which is 0.28-0.40 μm in the electromagnetic spectrum.

Vector: A quantity that has magnitude, direction, and sense. A vector is commonly represented by a directed line segment, with length representing magnitude and orientation in space representing direction. The length and orientation of the line segment has a conveyed meaning or sense.

Wavelength: In general, the mean distance between maximums (or minimums) of a roughly periodic pattern. Wavelength equals velocity per frequency.[1]

WRS: Worldwide Reference System.

Appendix B

Table B1.—USDA Forest Service remote sensing user's requirements, desired ground resolution and preferred film type, and recommendations for photographic remote sensing based on the state-of-the-art

Data user's requirements [1]			Current recommendations			
Data requirement	Ground resolution	Preferred film type	Smallest scale[2] Detection	Smallest scale[2] Measurement	Film type[4]	Platform[4]
	—m—		---Code Numbers[3]---			
I. Classification and mapping						
A. Vegetated cover						
1. Forest						
a. Trees (species)	0.1	CIR	4	2	Color	LAA
1) Seedlings	.1	CIR	4	2	Color	LAA
2) Saplings	.3	CIR	7	5	CIR	LAA
			9	6	Color	MAA,LAA
3) Poles and sawtimber	1.0	CIR	13	10	CIR	HAA
			17	13	Color	HAA
4) Mature	1.0	CIR	13	10	CIR	HAA
			17	13	Color	HAA
b. Stands	30.0	CIR	32	29	Color	SAT
2. Nonforest						
a. Shrubs (species)	.3	CIR	7	5	CIR	LAA
b. Stands	3.0	CIR	21	15	CIR	HAA
c. Forbs	.3	CIR	7	5	CIR	LAA
d. Stands	3.0	CIR	21	15	CIR	HAA
e. Grasses	.1	CIR	3	1	CIR	LAA
f. Stands	3.0	CIR	21	15	CIR	HAA
g. Aquatic	3.0	CIR	21	15	CIR	HAA
3. Forest wetlands	3.0	CIR	21	15	CIR	SAT
4. Floodplain vegetation	10.0	CIR	27	23	CIR	SAT
5. Estuary vegetation	.3	CIR	7	5	CIR	LAA
6. Impenetrable forest	.3	CIR	7	5	CIR	LAA
7. Fuel Type	5.0	CIR	24	19	CIR	HAA,SAT
a. Spacing						
b. Arrangement						
c. Kind						
d. Size						
e. Class						
f. Resistance						
g. Hazard type						
h. Fuel moisture						
B. Nonvegetated cover						
1. Rock (boulders, cobblestones, outcrops)						
a. Outcrop	3.0	CIR,Color	21	15	CIR	HAA
b. Cliffs-barriers	3.0	BW	21	15	CIR	HAA
2. Barren land						
a. Dunes and blowouts	3.0	CIR	21	15	CIR	HAA
b. Bare soil	.3	CIR	7	5	CIR	LAA
c. Extensive bare soil	10.0	CIR,Color	27	23	CIR	SAT
d. Element of bare soil in ground cover	.3	CIR	7	5	CIR	LAA

[1]Summarized from the USDA Forest Service Data User's Requirements Catalog, 1973-1976. However, some requirements have been modified to conform with current general knowledge.
[2]Smallest scale on which required information can be detected and measured on the recommended file.
[3]Codes to photographic scale, required magnification, and recommended instrument or methods of interpretation are given in table 2.
[4]Platform and film type (Eastman Kodak)
LAA – Low-altitude aircraft (150-3,660 m); Color 2445; CIR 2443; IR 2424; BW 3410
MAA – Medium-altitude aircraft (3,660-9,150 m); CIR 2443; IR 2424; BW 3410
HAA – High-altitude aircraft (9,150-19,820 m); CIR SO-127; Color SO-242; IR 2424; BW 3414
SAT – Satellite (over 190 km); CIR SO-127; Color SO-242; IR 2424; BW 3414

Table B1.—Continued

Data requirement	Ground resolution	Preferred film type	Smallest scale[2] Detection	Smallest scale[2] Measurement	Film type[4]	Platform[4]
	—m—		*———Code Numbers[3]———*			
e. Dry soil	1.0	CIR	11	9	CIR	MAA,HAA
f. Wet soil	1.0	Color	11	9	CIR	MAA,HAA
3. Water						
a. Eroded streams	3.0	BW	21	15	CIR	HAA
b. Bulldozed channels	3.0	IR,Color	21	15	CIR	HAA
c. Natural blockage	3.0	CIR	21	15	CIR	HAA
d. Locate estuaries	10.0	BW,IR,CIR	27	23	CIR	SAT
e. Water locate	3.0	BW	21	15	CIR	HAA
f. Surface level and running	3.0	IR	21	15	CIR	HAA
g. Hydrologic type	3.0	BW,IR,CIR	21	15	CIR	HAA
h. 1st and 2nd order streams	1.5	CIR	13	10	CIR	MAA,HAA
i. Water courses	3.0	Color,CIR	21	15	CIR	HAA
j. Delineate	3.0	BW,IR	21	15	CIR	HAA
C. Land use						
1. Condition prior to mining	3.0	BW	21	15	CIR	HAA
		IR,Color,CIR	25	20	Color	HAA,SAT
D. Landforms						
1. Landscapes	.3	BW,IR Color,CIR	9	6	BW	MAA,LAA
2. Physiography	.3	BW,IR Color,CIR	9	6	BW	MAA,LAA
3. Landscape texture	3.0	Color,CIR	21	15	CIR	HAA
4. Landscape color	3.0	Color,CIR	21	15	CIR	HAA
5. Landscape lines	3.0	Color,CIR	21	15	CIR	HAA
6. Landscape geomorphology	3.0	Color,CIR	21	15	CIR	HAA
7. Topography						
a. Elevations	.3	BW,IR, Color,CIR	9	6	BW	MAA,LAA
b. Maps	.3	BW,IR, Color,CIR	9	6	BW	MAA,LAA
c. Slopes	.3	BW,IR, Color,CIR	9	6	BW	MAA,LAA
d. Aspect	.3	BW,IR, Color,CIR	9	6	BW	MAA,LAA
e. Range suitability	.3	BW,IR, Color,CIR	9	6	BW	MAA,LAA
f. Terrain change	.3	BW,IR, Color,CIR	9	6	BW	MAA,LAA
g. Slope length	.3	BW,IR, Color,CIR	9	6	BW	MAA,LAA
h. Channel gradient	.3	BW,IR, Color,CIR	9	6	BW	MAA,LAA
i. Slope for range suitability	.1	BW	4	2	BW	LAA
8. Drainage	3.0	BW,IR	21	15	CIR	HAA
9. Watershed	3.0	Color,CIR	21	15	CIR	HAA
E. Disturbance						
1. Erosion	.5	BW,IR, Color,CIR	9	6	CIR	MAA,LAA
2. Severe erosion	1.0	BW,Color,CIR	11	9	CIR	MAA,HAA
3. Fire						
a. Structures threatened	3.0	BW,IR	21	15	CIR	HAA
b. Area burned	3.0	CIR	21	15	CIR	HAA
4. Insect Kill						
a. Blow down	5.0	IR	24	19	CIR	HAA,SAT
b. Down timber	2.0	BW	17	13	CIR	HAA
5. Fallen dead grass and forbs	.3	CIR	7	5	CIR	LAA
6. Ground cover litter	1.0	CIR	11	9	CIR	MAA,HAA
	.3	CIR	7	5		LAA
7. Snags, den trees	.3	CIR	7	5	CIR	LAA
8. Tree cause of death	.3	CIR	7	5	CIR	LAA
9. Mortality by species	.3	CIR	7	5	CIR	LAA

Column groups: Data user's requirements[1] (Data requirement, Ground resolution, Preferred film type); Current recommendations (Smallest scale, Film type, Platform).

Table B1.—Continued

Data user's requirements[1]			Current recommendations			
Data requirement	Ground resolution	Preferred film type	Smallest scale[2] Detection	Smallest scale[2] Measurement	Film type[4]	Platform[4]
	–m–		–––Code Numbers[3]–––			
10. Mortality by types	.3	—[5]	9	6	Color	MAA,LAA
11. Logged areas	10.0	Color	27	23	CIR	SAT
12. Logging residue	4.0	CIR	23	17	CIR	HAA,SAT
	.3	CIR	7	5	CIR	LAA
13. Disasters	3.0	—[5]	21	15	CIR	HAA
14. Mining	3.0	Color	21	15	CIR	HAA
a. Waste disposal	3.0	Color	21	15	CIR	HAA
b. Surface borrow pit	3.0	CIR				
15. Stand history	.3	CIR	9	6	Color	MAA,LAA
16. Trampled vegetation	2.0	CIR	17	13	CIR	HAA
17. Disturbed area	3.0	CIR	21	15	CIR	HAA
18. Urban development	3.0	CIR	21	15	CIR	HAA
19. Type of disturbance	3.0	CIR	21	15	CIR	HAA
20. Drainage facility failure	.3	CIR	7	5	CIR	LAA
21. Water resource						
a. Floating debris	3.0	BW,CIR	21	15	CIR	HAA
b. Sediment movement	3.0	Color	21	15	CIR	HAA
c. Plankton, algae	3.0	CIR	21	15	CIR	HAA
22. Disaster						
a. Fire, flood and earthquake	.5	BW,IR Color,CIR	9	6	CIR	MAA,LAA
II. Interpretive Information for Specific Applications						
A. Land use (major)						
1. Urban areas	3.0	CIR	21	15	CIR	HAA
2. Recreational	3.0	BW,Color,CIR	25	20	Color	HAA,SAT
3. Pavement ground cover	1.0	CIR	11	9	CIR	HAA,MAA
B. Wildlife habitat						
1. Forest edge	30.0	—[5]	32	29	CIR	SAT
2. Forest-agric. edge	30.0	—[5]	32	29	CIR	SAT
3. Forest-aband. edge	10.0	—[5]	27	15	CIR	SAT
4. Forest-stream edge	3.0	—[5]	21	15	CIR	HAA
5. Forest-ocean edge	30.0	—[5]	32	29	CIR	SAT
6. Forest-water edge	10.0	—[5]	27	23	CIR	SAT
C. Land use (vegetation)	1.5	CIR	13	10	CIR	MAA,HAA
D. Fire utilization corridors	3.0	BW	21	15	CIR	HAA
E. Fuel type	5.0	CIR	24	19	CIR	HAA,SAT
F. Grazeable woodland	.3	CIR	9	6	Color	MAA,LAA
G. Vegetative condition						
1. Insect effect	.3	CIR	7	5	CIR	LAA
2. Disease effect	2.0	BW	17	13	CIR	HAA
3. Disease	80.0	BW,	36	33	CIR	SAT
		IR,Color,CIR	36	33	MB[6]	SAT
4. Wildlife	.3	CIR	9	6	Color	MAA,LAA
5. Pollution effect	.3	Color	7	5	CIR	LAA
			9	6		
H. Unstable conditions						
1. Unstable areas	.5	BW	9	6	CIR	MAA,LAA
		IR,Color,CIR	10	8	BW	HAA,LAA
I. Rock slide barriers	.5	BW	9	6	CIR	MAA,LAA
		IR,Color,CIR	10	8	BW	HAA,MAA
J. Avalanche path	.5	BW	9	6	CIR	MAA,LAA
		Color,CIR				
K. Geology						
1. Geologic structure	3.0	Color,CIR	21	15	CIR	HAA
2. Identify rock	3.0	Color,CIR	21	15	CIR	HAA
3. Describe rock structure	3.0	Color,CIR	21	15	CIR	HAA
4. Fault lines	3.0	Color	21	15	CIR	HAA

[5]*Ground resolution was estimated. No preferred film type was given in the User's Requirements Catalog.*
[6]*Multiband photographs BW 3414 and IR 2424 films with appropriate filters.*

Table B1.—Continued

Data user's requirements [1]			Current recommendations			
Data requirement	Ground resolution	Preferred film type	Smallest scale[2] Detection	Smallest scale[2] Measurement	Film type[4]	Platform[4]
	–m–		---Code Numbers[3]---			
L. Soil						
1. Low intensity units	0.5	BW,IR Color,CIR	10	8	BW	HAA,MAA
2. Soil classes and associations	.5	BW	10	8	Color	HAA,MAA
		IR,Color,CIR	9	6	IR	MAA,LAA
M. Minerals and construction materials						
1. Gravel	3.0	Color,CIR	21	15	CIR	HAA
2. Location and extent	3.0	Color	25	20	Color	HAA,SAT
		CIR	21	15	CIR	HAA
N. Phenology						
1. Leafing	.3	CIR	7	5	CIR	LAA
2. Defoliation	.3	CIR	7	5	CIR	LAA
3. Phenological stage	.3	CIR	7	5	CIR	LAA
O. Tree point occupied	.3	CIR	9	6	BW	MAA,LAA
P. Senescent or dystrophic lakes	2.0	Color,CIR	17	13	CIR	HAA
Q. Hydrological condition	10.0	BW,IR,CIR	27	23	CIR	SAT
R. Natural open areas	3.0	BW,IR, Color,CIR	21	15	CIR	HAA
III. Measurements of Resource Parameters						
A. Tree and stand						
1. Tree						
a. Height	.3	CIR	9	6	BW,Color	MAA,LAA
b. Basal area	.3	CIR	9	6	BW,Color	MAA,LAA
c. Diameter	.3	CIR	9	6	BW,Color	MAA,LAA
d. Crown length	.3	CIR	9	6	BW,Color	MAA,LAA
e. Crown diameter	.3	CIR	9	6	BW,Color	MAA,LAA
f. Sawlog length	.3	CIR	9	6	BW,Color	MAA,LAA
g. Age	.3	CIR	9	6	BW,Color	MAA,LAA
h. Crown class	.3	CIR	9	6	BW,Color	MAA,LAA
i. Bole length	.3	CIR	9	6	BW,Color	MAA,LAA
j. Annual growth	.3	CIR	9	6	BW,Color	MAA,LAA
k. Crown ratio	.3	CIR	9	6	BW,Color	MAA,LAA
l. Tree age class	1.0	CIR	11	9	CIR	HAA,MAA
2. Stand						
a. Height class	.3	CIR	9	6	BW,Color	MAA,LAA
b. Mean diameter	.3	CIR	9	6	BW,Color	MAA,LAA
c. Crown cover by species group	.3	CIR	9	6	BW,Color	MAA,LAA
d. Tree count by stand	.3	CIR	9	6	BW,Color	MAA,LAA
e. Crown cover (generalized)	3.0	BW,IR	25	20	BW	HAA,SAT
f. Tree Count	.3	CIR	9	6	BW,Color	HAA,SAT
g. Site	5.0	CIR	24	19	CIR	HAA,SAT
h. Volume	5.0	CIR	24	19	CIR	HAA,SAT
i. Accumulated growth	.3	CIR	7	5	CIR	LAA
3. Forest						
a. Percent forest with vegetation	.3	CIR	7	5	CIR	LAA
B. Grasses						
1. Age	3.0	BW,IR	21	15	CIR	HAA
2. Form class	3.0	Color,CIR	21	15	CIR	HAA
C. Forbs						
1. Form class	3.0	BW,IR, Color,CIR	21	15	CIR	HAA
D. Brush and shrubs	.3	CIR	9	6	Color	MAA,LAA
1. Diameter						
2. Basal area						
3. Height						
4. Form class						
E. Water						
1. Stream width	.3	BW	7	5	CIR	LAA
		IR	7	5	IR	LAA
2. Stream length	3.0	BW	21	15	CIR	HAA
		IR	17	13	IR	HAA

Table B1.—Continued

Data user's requirements [1]			Current recommendations			
Data requirement	Ground resolution	Preferred film type	Smallest scale[2] Detection	Smallest scale[2] Measurement	Film type[4]	Platform[4]
	–m–		–––Code Numbers[3]–––			
3. Size and shape	10.0	BW	27	23	CIR	HAA,SAT
		IR,Color,CIR			IR	HAA,SAT
4. Acre feet	3.0	BW,IR	25	20	BW	HAA,SAT
5. Depth	.1	Color,CIR	4	2	Color	LAA
6. Dissolved matter	3.0	CIR	21	15	CIR	HAA
7. Algae and plankton	3.0	Color,CIR	21	15	CIR	HAA
F. Snow						
1. Area	10.0	—[5]	27	23	CIR	SAT
G. Rock slides						
1. Confirmation	.5	BW,IR, Color,CIR	9	6	CIR	MAA,LAA
2. Suspected	10.0	BW,IR, Color,CIR	27	23	CIR	HAA,SAT
H. Gully erosion						
1. Length, width, depth	.2	BW,IR, Color,CIR	6	4	CIR	LAA
I. Sheet erosion						
1. Area	.5	BW,IR, Color,CIR	9	6	CIR	MAA,LAA
J. Biomass	.3	CIR	7	5	CIR	LAA
1. Annual production						
2. Standing crop						
3. Usable growth						
4. Plant density						
5. Accumulated growth (horizontal)						
6. Vegetation distribution						
7. Annual growth for area						
8. Flora by species, number and size						
9. Vegetated area						
K. Land use						
1. Area of pavement	1.0	CIR	11	9	CIR	HAA,MAA
2. Area	3.0	CIR	21	15	CIR	HAA
L. Disturbed area	3.0	CIR	21	15	CIR	HAA
M. Area of mortality	.3	CIR	9	6	Color	MAA,LAA
N. Animal counts	.3	BW,IR, Color,CIR	9	6	BW	MAA,LAA
1. Cattle						
2. Sheep						
3. Horses						
4. Burros						
O. Fuel						
1. Volume	5.0	CIR	24	19	CIR	HAA
P. Fire area burned	10.0	BW,IR, Color,CIR	27	23	CIR	SAT
Q. Dimension of structures (improvements)	.3	CIR	9	6	BW	MAA,LAA
IV. Observations and Counts of Occurrences						
A. Buildings and structures	.3	BW	7	5	CIR	LAA
1. Fences	.3	IR	7	5	CIR	LAA
2. Bridges and culverts	.3	Color,CIR	7	5	CIR	LAA
3. Works of men	.3	BW,IR, Color,CIR	7	5	CIR	LAA
4. Structural range improvements	.3	CIR	7	5	CIR	LAA
B. Water structures						
1. Canals and ditches	5.0	BW,IR,CIR	24	19	CIR	HAA,SAT
C. Transportation						
1. Woods roads	1.0	BW,Color,CIR	11	9	CIR	HAA,MAA
2. Abandoned roads	.5	BW,Color	9	6	CIR	MAA,LAA
and trails	3.0	BW,Color,CIR	21	15	CIR	HAA
3. Road location	3.0	BW,IR, Color,CIR	21	21	CIR	HAA

Table B1.—Continued

Data user's requirements [1]			Current recommendations			
Data requirement	Ground resolution	Preferred film type	Smallest scale[2] Detection	Smallest scale[2] Measurement	Film type[4]	Platform[4]
	–m–		*–––Code*	*Numbers[3]–––*		
D. Recreation						
1. Marine craft	1.5	BW,IR, Color,CIR	13	10	CIR	HAA
2. Archaeological sites	5.0	BW,Color	24	19	CIR	HAA,SAT
	15.0	CIR	29	26	CIR	SAT
3. Count people in or with boats	.1	BW	3	1	CIR	LAA
4. Count people in or with recreation vehicles	1.0	BW,IR, Color,CIR	13	10	Color	HAA
5. Count people by recreation activity	1.0	BW,IR, Color,CIR	13	10	Color	HAA
6. Forest visitors by vehicle or pedestrian	.5	BW	10	8	Color	HAA,MAA
7. Count people in camps	1	BW,Color	4	2	Color	LAA
8. Count people with autos	1	BW,Color	4	2	Color	LAA
9. Count people with boats	1	BW,Color	4	2	Color	LAA
E. Wildlife						
1. Bald eagle nest trees	1.0	CIR	11	9	CIR	HAA,MAA
2. Wild horse-burro use area	3.0	CIR	21	15	CIR	HAA

Aldrich, Robert C. 1979. Remote sensing of wildland resources: A state-of-the-art review. USDA For. Serv. Gen. Tech. Rep. RM-71, 56 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

A review, with literature citations, of current remote sensing technology, applications, and costs for wildland resource management, including collection, interpretation, and processing of data gathered through photographic and nonphotographic techniques for classification and mapping, interpretive information for specific applications, measurement of resource parameters, and observations and counts of occurrences.

Keywords: Remote sensing, photographic, nonphotographic, classification, mapping, interpretation, measurements, observations, wildland, forest, range, soils, water

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A review, with literature citations, of current remote sensing technology, applications, and costs for wildland resource management, including collection, interpretation, and processing of data gathered through photographic and nonphotographic techniques for classification and mapping, interpretive information for specific applications, measurement of resource parameters, and observations and counts of occurrences.

Keywords: Remote sensing, photographic, nonphotographic, classification, mapping, interpretation, measurements, observations, wildland, forest, range, soils, water

U.S. Department of Agriculture
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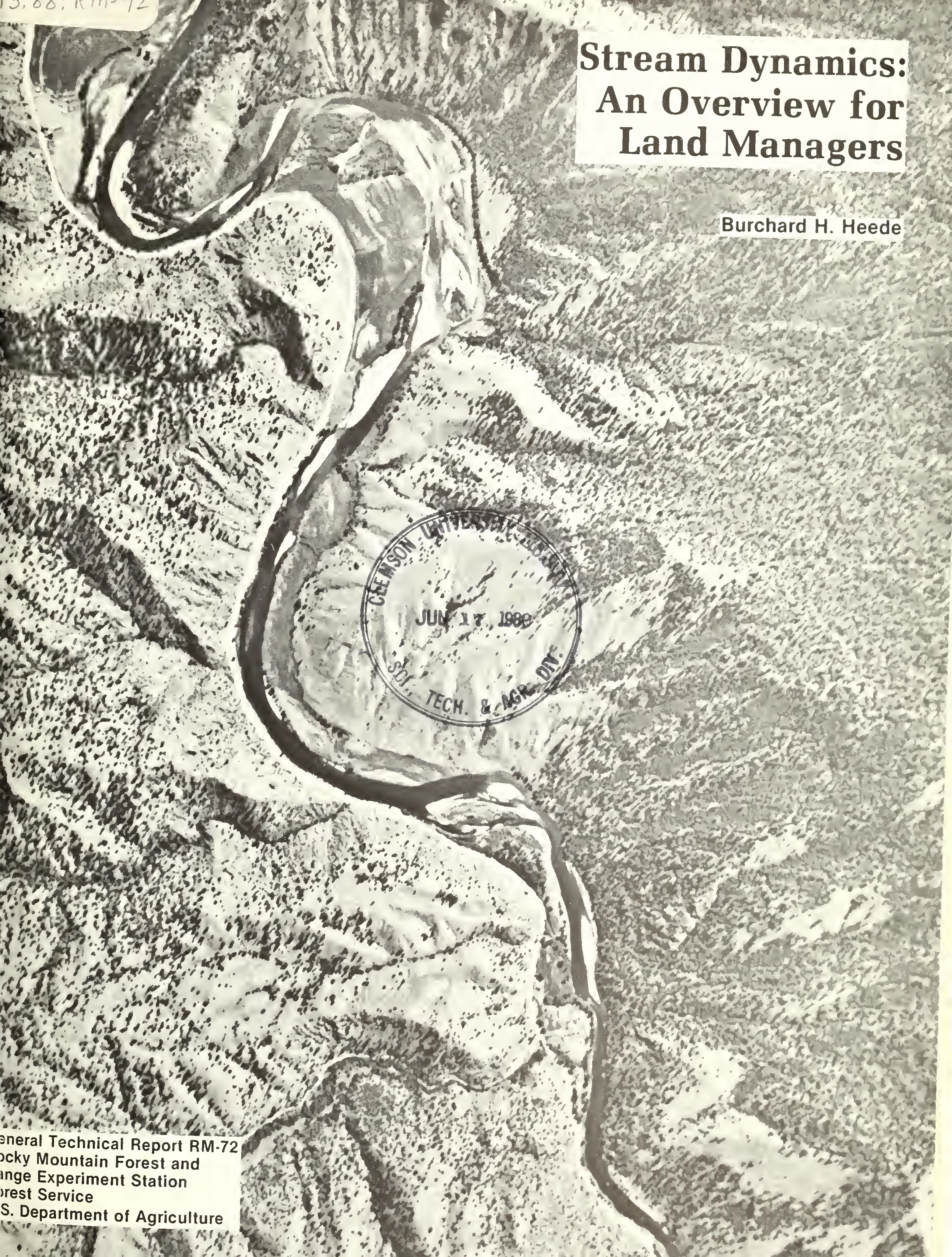
Stream Dynamics: An Overview for Land Managers

Burchard H. Heede



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Abstract

Concepts of stream dynamics are demonstrated through discussion of processes and process indicators; theory is included only where helpful to explain concepts. Present knowledge allows only qualitative prediction of stream behavior. However, such predictions show how management actions will affect the stream and its environment.

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Stream Dynamics: An Overview for Land Managers

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Stream Dynamics: An Overview for Land Managers

Burchard H. Heede

INTRODUCTION

Scope and Purpose

A land manager should understand general concepts of stream behavior to be aware of how management actions affect streams, since such actions can influence streams drastically. For example, vegetation cover manipulations on a watershed can increase water yield (Hibbert 1971), or streamside forest removal can activate bedload transport (Heede 1977). Streams are dynamic systems that are prone to change even without human interference (Heede 1975); change in the system itself may bring about adjustment once a geomorphic threshold has been reached (Schumm 1974). Thus, land management-stream interactions are complex.

Other professionals who need a general understanding of fluvial processes are hydrologists, civil engineers, fishery biologists, and plant biologists. Plant biologists might be concerned with riparian vegetation interactions with the stream, while the fishery biologist works in the stream itself. The hydrologist, on the other hand, is concerned with precipitation input into a watershed, its concentration in channels, and the mode, quantity, and quality of flow discharge. The civil engineer is more likely to be concerned about scour at bridge piers (degradation), or loss of discharge capacity by deposition (aggradation).

Knowledge of stream dynamics will help to point out what information is needed to characterize stream conditions, and what indicators suggest about present and future stream behavior. With this knowledge, professionals engaged in land management will be able to estimate what, where, and when effects of their actions will take place.

General understanding of fluvial concepts should also help managers recognize if a particular situation demands attention from an expert in river science (a potamologist). Unfortunately in many situations, stream data are either nonexistent or cover only flow rates and yields, but do not characterize present conditions or make well founded projections possible (Heede 1979).

High- and low-flow conditions have different requirements for conveyance of the water. If flow changes drastically, the channel often does not meet the new requirements, and adjustments must be made through stream-erosion processes. Well known examples are channel bed degradation or channel meandering.

This report presents a general outline of water flow and sediment transport as basic to all channel changes. It describes stream equilibrium condition and the required adjustment processes if equilibrium is lost. These processes lead to alignment, shape, or profile changes.

The user should be acquainted with the basics of flow and sediment transport and should recognize the strong interdependency between practically all hydraulic variables. Arrangement of this text permits the reader to consider only those processes of interest. The Literature Cited section will suffice or provide a starting point for in-depth study of specific processes or theories.

Characteristics of Streams

We usually think of a stream as one entity with a specific characteristic, such as the mighty Mississippi, the unpredictable Platte River, a small artery of a large stream system, or a bubbling mountain brook. But these same streams are very different at different times. At high-flow stage, for instance, mountain brooks are anything but bubbling waters. At low-flow regime, they meander sluggishly between channel banks, often filling not more than a fraction of the total bed. But at high-flow regime or flood stage, the channel may be totally filled or even too small, flood plains become water covered, and meanders straighten to convey the rushing waters most quickly.

If we would analyze the hydraulic variables of these two types of flow, we would have to conclude the character assigned to the stream is based on a single aspect and not on its complexity, because two different streams may be represented if low- and high-flow regimes are considered. Although the argument may appear merely semantic, in reality it is deep seated, since different processes are operative in both streams. Even to the casual observer, stream systems are dynamic.

THE BASIC FLUVIAL PROCESS

Subcritical Versus Supercritical Flow

Natural streams convey their water in different modes. At times, or in certain channel reaches, the flow is tranquil (subcritical) exerting low energies on banks and bed; at others, shooting (supercritical) flows occur which energies may damage an unprotected channel. Human activities can cause undesirable high-energy (supercritical) flows. For example, encroachments into the channel by diversion structures or bank revetments can narrow the channel. As a

consequence, the area of flow may decrease to the point where shooting flows occur. Knowledge of flow regimes, describing the flow characteristics in terms of available energies, therefore is required to recognize problems in channels or proposed channel improvements.

Fortunately, subcritical flow is the more common type of flow (fig. 1). Available energy of such flows is less than that of supercritical flows of the same discharge. The total energy of a flow (total head of flow) can therefore be better conserved in subcritical flow (Koloseus 1971). Maintenance of total head is important for channel stability as well as for structures such as water diversions.

In contrast, supercritical flow is undesirable because of its great erosive power due to high velocities (fig. 2). Also, higher stagnation pressures of supercritical flows can develop uplift forces of such magnitude that canal linings and concrete diversion structures have been removed (fig. 3) (Koloseus 1971). Stagnation pressure is the sum of the pressure intensity in a zone of uniform motion and the rise in pressure intensity due to channel obstruction or other changes.

Supercritical flows can also cause standing waves, produced when two equal waves travel in opposing directions. Standing waves may reach magnitudes requiring prohibitively high canal walls or diversion ditchbanks. Standing waves must also be considered where narrowing of channels by human works is planned. As a general rule, stream reaches with supercritical (shooting) flow should be avoided for structural installations, and this type of flow should not be created by channel manipulations (narrowing).

Froude Number

The Froude number (Fr), a dimensionless parameter, offers a quantitative measure to determine if subcritical or supercritical flow will occur. This number represents the ratio of inertial to the gravitational forces and is given by:

Figure 1.—Downstream view of the Verde River north of Phoenix, Ariz. The flow is subcritical (tranquil).

$$Fr = \frac{V}{\sqrt{gd}}$$

where V is the average velocity in the cross section of measurement, g if the acceleration due to gravity, and d is the average water depth. If inertia is smaller than the gravitational force, $Fr<1$, and flow will be subcritical (fig. 1), the flow will be supercritical if the ratio reverses and $Fr>1$. Critical flow, required for many artificial stream-gaging stations, has a Froude number of 1, but seldom will occur in natural channels. This regime is very unstable and generally occurs only for very short periods of time as a transitional stage between tranquil and shooting flows. While subcritical flows will show a relatively smooth water surface except for waves created by winds or some protrusions, supercritical flows exhibit surface waves that travel upstream (fig. 2).

Laminar Versus Turbulent Flow

Flows can also be characterized by the movements of individual fluid elements with respect to each other, which result in either laminar or turbulent flow. The major distinction is that, in turbulent flows, a complex secondary motion is superimposed on the primary (laminar) motion of the fluid elements (Rouse 1950).

In laminar flow, each fluid element moves in a straight line with uniform velocity. There is no diffusion between the layers or elements of flow, and thus no turbulence. In contrast, turbulent flow has a complicated pattern of eddies, producing random velocity fluctuations in all directions. These are caused by continuous interchange of finite masses of fluid between neighboring zones of flow. The phenomenon results in a disruption of the entire flow pattern; a current meter immersed in a turbulent stream shows continual deviations from the mean value. Obviously, constant changes of flow lines lead to surges of flow against banks and structures, increasing flow impacts. Turbulent flow is the normal condition in streams.

Reynolds Number

Movements of the fluid elements depend on the inertial and viscous forces. The latter, in a loose sense, could be envisioned as an expression of internal friction of the flow. The Reynolds number (Re) is a dimensionless measure of these forces:

$$Re = \frac{Vd}{\nu} = \frac{\text{inertial force}}{\text{viscous force}}$$

where ν is the kinematic viscosity represented by the ratio μ/ϱ; μ is the absolute viscosity and ϱ the fluid density. For natural channels, the critical value dividing laminar from turbulent flow is near a Reynolds number of 2,000; values less than 2,000 generally indicate laminar and those over 2,000 indicate turbulent flow.

Figure 2.—Shooting flow in a constricted segment of the Salmon River, Idaho. The view is downstream. Note waves are traveling upstream (toward the viewer).

In summary, most natural streams have subcritical flow ($Fr = <1$). Also, turbulent flow ($Re = >2,000$) prevails over laminar flow ($Re = <2,000$).

Sediment Transport

Sediment transport is very complex. At least 30 variables are locked into the sedimentation processes, and the degree of interdependency between these variables is not fully understood. It is not surprising, therefore, that a reliable numerical method for determining bedload transport in alluvial streams is not yet available (Bogardi 1974, p. 17). Available methods are based on empirical relationships between a selected number of variables or require prerequisites based on assumptions not necessarily valid for the conditions.

Figure 3.—High stagnation pressures from shooting flows of the unusual January 1979 flood in the Verde River, central Arizona, created uplift forces that aided in upsetting this water-diversion structure and a 2-foot-diameter concrete pipeline.

For stable channels, Lane (1955a) demonstrated the qualitative relationships between sediment discharge (Q_s) and water discharge (Q_w) as a balance (fig. 4)

$$Q_s D \propto Q_w S$$

where D is the sediment particle size and S represents the slope. Lane's balance illustrates the intricate stream adjustment processes. If one side of the balance changes, the other must adjust to maintain equilibrium. Thus alterations in sediment or water discharge require changes in grain size and/or slope. For example, if the slope is increased, the stream will attempt to transport larger particles, or if stream discharge decreases, sediment load must decrease also to maintain balance. Otherwise, degradation or aggradation of the streambed will occur, respectively, as indicated by the figure.

For his balance, Lane selected as sediment discharge (Q_s) the coarser part of the sediment load, or more exactly the bed material load. He defined bed material load as the sediment in transport of sizes readily available in considerable quantities in the streambed. It is the coarser material largely molding the bed formation. He argued, "in most cases, the quantity of the fine load of silt and clay sizes can change almost indefinitely without materially affecting the river profile." We know now there are exceptions to this rule, such as when extremely large loads of fine material (wash load) are available. Heavy concentrations of fines cause a higher apparent viscosity of the fluid, which in turn results in increased transport

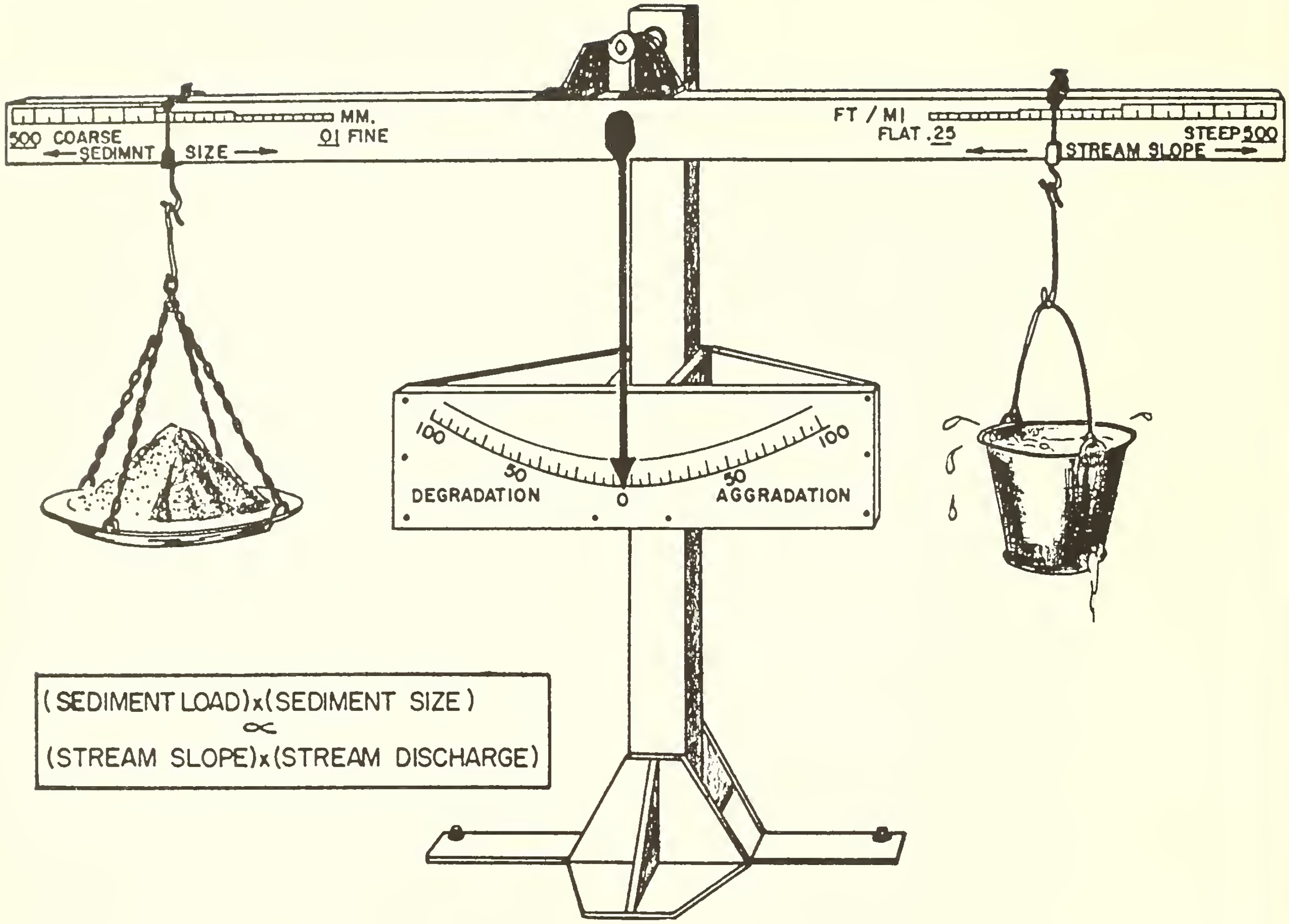


Figure 4.—Stable channel balance. (Sediment loads times sediment size) varies as (stream slope times stream discharge). (Courtesy of the American Society of Civil Engineers; from Lane, E. W. 1955. The importance of fluvial morphology in hydraulic engineering. American Society of Civil Engineers Proceedings, Hydraulic Division 81:745-1 to 745-17.)

capacity for sediment. More and larger particles can be transported, which in turn affect the stream profile. An extreme condition, illustrating the viscosity influence (Bull 1968) in addition to the relatively high specific gravity of the flow mixture (Crandell 1968), is a mudflow carrying room-size boulders like soap bubbles. Johnson (1970, p. 461) suggested that lift forces may also be involved.

Flume experiments by Simons et al. (1963) demonstrated that clay in suspension affects viscosity, bed form, and flow resistance. With clay suspension, the total sediment load increased, which in turn affected the bed form. Since bed forms influence flow resistance (Simons and Richardson 1966), they enter directly into the hydraulics of the flow. Again, the interdependency of the processes illustrates the difficulty, if not impossibility, of quantitatively predicting the stream environment.

Water temperature also influences sediment transport capacity more than many investigators recognize. As temperature decreases, viscosity increases, and carrying capacity increases (Colby 1964). For example, when Colby dropped water temperature from 80° to 40° F, the sediment discharge for sand sizes ranging from 0.125 to 0.250 mm increased by 254%. The size class is common for riverbed sand.

Field investigations confirmed the temperature-sediment transport relations and their vital influence on stream behavior. In the Lower Colorado River for a given discharge, the sediment loads were 2.5 times greater in winter than in summer (Lane et al. 1949). Fahnestock and Maddock (1964) reported a change in water temperature of about 35° F from March to August significantly affected the hydraulics of flow and bed form in the Rio Grande River near El Paso, Tex. At some similar discharges, mean velocity was greater in March and the bed was plane, whereas mean velocity was less in August and large dunes developed on the bed (flow resistance increased with dune formation).

Management implications based on the temperature-sediment relations are many. Where data on annual sediment loads are required, best results will be

obtained by sampling during summer and winter. Winter data of one stream should not be related to summer data of another. Most land management actions result in increased water temperatures and, therefore, decreased sediment loads. Under extreme conditions, this could lead to aggradation.

From many observations it has been found the sediment load in natural streams varies roughly as the square of the discharge (Lane et al. 1949). This approximation is expressed by the equation

$$Q_s = K_a Q^2_w$$

where Q_s is the sediment load in tons per day, Q_w represents the water discharge in cubic feet per second, and K_a is a coefficient that normally changes from stream to stream and with the season. The K_a coefficient could be helpful for approximating future sediment loads if used with flow frequency curves (differentiated between winter and summer flows), because some probabilistic aspects of sedimentation would be taken care of. Because the variation in the original data will generally be large, long periods of record are required to obtain meaningful averages. The length of record required depends on the degree of uniformity in the particular stream system.

Differences between sediment transport capacity and actual sediment load lead to deposition or scour (Lane 1955b). In other words, sediment is stored or depleted in a given reach, resulting in nonuniform flow of sediment. Uniform sediment flow represents equilibrium condition and satisfies the continuity principle of sediment (Vanoni et al. 1961). If actual sediment discharge differs from the equilibrium sediment discharge, the stream will try to adjust the actual to the equilibrium discharge. Both the actual rate of transport and the equilibrium rate will change, but they will tend to approach each other. Uniformity of sediment discharge must be considered over time, because sediment often moves in a wave-like mode, especially if movable bed forms such as dunes are present.

In many instances, works of humans distort uniform sediment flow. Best known examples are river dams causing a decrease of equilibrium transport rate upstream from the reservoir (backwater zone), and a decrease of actual transport rate below the dam. While aggradation takes place in the backwater zone, the "starved" stream picks up material from the bed downstream from the dam to satisfy the equilibrium requirement.

Vanoni et al. (1961) roughly categorized river engineering problems caused by nonuniform sediment transport. When the actual transport rate is larger than the equilibrium rate (deposition), the following occur:

1. Aggradation upstream from a reservoir.
2. Sedimentation in reservoirs and lakes.
3. Tributary channels bring heavy sediment loads to the main channel, causing local aggradation (examples are fan formation and tributary bar) (fig. 5).
4. Canyon streams discharge on alluvial fans, causing widespread deposition (as in Los Angeles area).
5. Desilting works at water intakes that return all sediment load to the main channel, in which flow of water is depleted, lead to aggradation (e.g., Im-

Figure 5.—A tributary contributed heavy sediment loads to Sycamore Creek, northeast of Phoenix, Ariz. These loads could not be carried by the main stream, and an alluvial fan developed, pushing the flow into the opposite bank. Sycamore Creek flows from right to left.

perial Dam). Remaining flow magnitudes provided a small equilibrium transport rate compared with the original flow.

6. Where river regulation eliminates floods that formerly cleared the channel of accumulated sediment and vegetation periodically, aggradation results in the clogged channel (e.g., Colorado River at Needles).

When the actual transport rate is smaller than the equilibrium rate (scour), the following occur:

1. Degradation downstream from dams that trap sediment and thus decrease the actual transport rate.
2. Canals receiving clear water will scour if the bed material is fine enough that it can be picked up readily by the flow. Under such conditions, the equilibrium transport rate is large, while the actual transport rate of the flow entering the canal is essentially zero.
3. Channel realignments that increase the slope also increase the equilibrium transport rate because of increased flow velocities.

Interdependency of Hydraulic Variables

The complexity of hydraulic variables is immense. Lane (1957) singled out eight variables of this complex which he called most important: (1) stream discharge, (2) longitudinal slope, (3) sediment load, (4) resistance of banks and bed to movement of flowing water, (5) vegetation, (6) temperature, (7) geology, and (8) works of humans. The interrelationships among longitudinal profile, sediment load, and resistance of the banks and bed to movement are particularly close and complex.

Interdependency between many variables often precludes the establishment of one-value relationships. For example, Brooks (1958) found neither the velocity nor the sediment discharge concentration could be expressed as a single-valued function of the bed shear stress, or any combination of depth and slope, or hydraulic radius and slope. He showed experimentally that flow with a given depth and slope can occur with at least two velocities. This is due to changeable bed configuration which causes large variations in the channel roughness. Thus if one or a combination of the interdependent factors change under the impact of external or internal forces, adjustment of one, some, or all of the components will follow.

It is important to recognize that established relationships between most interdependent variables, except for basic factors such as the shear, are empirical and thus not necessarily applicable for a wide range of conditions. Examples are Blench's (1966) equations based on the concept of the regime theory, originally developed by Lindley (1919) and Lacey (1932) for Indian canals. This theory assumes there exists only one type of cross section for a given stream with a given load. Thus width and depth of the channel are the main parameters in the equations. Attempts to reduce the complex stream situation by empirical relationships between a few variables are still pursued (Osterkamp 1977). Obviously, such relationships will be valid only for the area of their origin.

The complexity of the fluvial system suggests stream analysis is a probabilistic problem. Because of the interaction between channel bed, banks, and flow, the core of the problem appears to be the random distribution of the flow energy ($mV^2/2$), where m is the mass of water. The velocity must be recognized as a vector force (i.e., it has direction). Because of turbulent flow in most natural streams, this direction occurs randomly. Thus the energy, itself of stochastic nature, acts on randomly distributed sediment particles. Incipient particle motion is therefore a very complicated event and no satisfactory way of determining it has been found. Sediment transport is a fundamental variable in stream dynamics.

EQUILIBRIUM CONDITION AND ADJUSTMENT PROCESSES

Dynamic Equilibrium

The concept of dynamic equilibrium is very useful in evaluating stream systems and their stage of development. This concept does not imply absolute equilibrium conditions, but that the stream can adjust to a new hydraulic situation within a relatively short time, perhaps within a few years. Obviously, if considered in geologic time spans, dynamic equilibrium has no place, because land denudation is the long-term process. Although dynamic equilibrium cannot be well defined, the investigator can use indicators, some of which are readily recognizable in the channel, to analyze stream stability in terms of equilibrium condition.

Heede (1975) listed several factors indicative of small mountain streams not in dynamic equilibrium: channel headcuts, under-developed drainage nets such as those having channelized water courses only on one-half or less of the watershed area, frequent bedscarps, and the absence of a concave longitudinal profile where watershed conditions are relatively constant. The last condition will depend mainly on geologic homogeneity, availability of bedrock outcrop, and tributaries. When surveying a channel, select a reach with sufficient length to avoid distortion of the overall shape of the longitudinal profile by local irregularities. This length will vary with size of stream. In small mountain streams, lengths of at least 0.25 mile should be sampled in the headwater, middle, and lower reaches. Obviously, greater lengths will improve the representativeness of the profile.

Channel headcuts are local erosion sources because headcuts advance upstream. They indicate that stream length and gradients have not been developed to allow equilibrium condition. Bedscarps that develop at channel nickpoints similarly indicate pronounced breaks

in longitudinal gradients. These scarps proceed upstream until a smooth transition between upstream and downstream gradient is attained. Thus, headcuts and bedscarps substantially add to the sediment load because erosion will be severe until natural channelization is achieved and the longitudinal profile "smoothened." Actual sediment production rates higher than the equilibrium transport rate require steepening of the slope, normally attained by bed aggradation. Since aggradation processes are slow, such a stream must be judged out of dynamic equilibrium because of the long time required for reestablishment of this condition.

Streams in dynamic equilibrium have no headcuts. Their watercourse begins high up on the watershed with a smooth transition from the unchannelized area to the channel. Bedscarps, not developed at locations of rock outcrop or variations in bedrock, are absent or few. As a result, sediment production is negligible. The longitudinal profile is concave. Generally, flow, depth, width, and velocity increase downstream while gradient and sediment particle size decrease if watershed conditions are relatively constant over long stream reaches.

Complex Channel Response

Streams respond to an upset of a given equilibrium condition by different adjustment processes. These processes follow a sequence if considered in terms of relative time and energy expenditures. Channel adjustments, ordered from small to large energy requirements, involve changes in: bed form, bed armor, width, pattern (alignment), and longitudinal profile.

Generally, bed form changes require the least amount of energy and time. Examples of bed forms are dunes in sand bed or gravel bars in boulder-strewn streams. Bed forms determine resistance to flow (bed roughness) (Simons and Richardson 1966). Thus their change (i.e., from a dune to an anti-dune) may be sufficient to achieve adjustment. A dune is a sand wave of approximately triangular cross section in the direction of flow. It has a gentle upstream slope and a steep downstream slope. The dune travels downstream by the upward movement of the sediment on the upstream slope and the deposition of it on the downstream slope.

An antidune is a sand wave, indicated by a regular undulating water-surface wave. Usually, antidunes and accompanying surface waves occur in trains of 3 to 20 or more. If the antidunes move at all, it is upstream. The surface waves become gradually steeper on their upstream sides until they break like a surf and disappear. Often they reform after disappearing.

Where a change in form roughness is not sufficient or is impossible, additional or different processes will be required to attain a new equilibrium condition. An additional process may be armor plating of the bed. It will require more time than bed form change.

If armoring is not possible because of grain size distribution or insufficient amounts of large material, channel width changes generally would be the next adjustment process. Width increases signify increases in the wetted perimeter of the flow, leading to larger roughness of flow and smaller flow velocities. As a consequence, available energies are decreased.

Even width changes may not bring about the required adjustment. The next most energy- and time-consuming process would be channel pattern change to meander or braiding. If topographic and hydraulic conditions do not allow this change, as will be discussed in a later section, bed profile alterations will begin. Generally, these demand the greatest energy expenditures as well as the longest time of all adjustment processes.

Geology, soils, and vegetation also enter into the selective adjustment processes because of their influence on bank and bed stability and hence on sediment transport. Thus they add to the complexity of stream response. One must realize, therefore, an orderly succession of processes, as outlined, may not operate in streams seeking new equilibrium conditions; the most energy-intensive process could be operating by itself. In short, the purpose of the above discussion is to show relative energy and time expenditures between different adjustment responses.

MAJOR ADJUSTMENT PROCESSES

Management activities may trigger or change channel adjustment processes. It is important, therefore, to recognize the adjustment criteria and factors which must be addressed when evaluating management activities in terms of impact on streams.

Five major channel adjustments were outlined in terms of required energy expenditures in the preceding section. The processes responsible for those adjustments are sometimes grouped into two categories: one affecting channel pattern and shape, the other affecting the longitudinal profile. Channel pattern refers to the plan view of a stream and its alignment, while channel shape relates to the cross-sectional view across the channel.

Some processes are reponsible for more than one type of adjustment, however. Thus, bar formation processes may bring about three types of adjustment: in pattern, shape, and longitudinal profile. In a straight reach, for example, alternate bars force the thalweg (line of maximum depth) into a meander pattern. This, in turn, leads to increased stream length and longitudinal profile changes, as well as to changes of the channel cross section. It is also obvious that aggradation or degradation processes change not only the stream's longitudinal profile but also its cross sections. The division of the processes into two categories is therefore a shortcoming of most of our classification systems, but it is accepted for convenience. The relationship between one process and multiple forms demonstrates again the complexity of stream systems.

Four processes affecting channel pattern and shape are recognized. They lead to bar formation, channel patterns, cross-sectional channel shapes, and types of banks.

Different types of bars develop in natural streams. All are integrated into the stream hydraulics and are therefore not necessarily stationary, since most streams change their flows with season and individual events. Each type occurs in a given situation, and hence is an indicator of prevailing flow and channel conditions, as will be discussed in the following section.

Channel patterns are very diversified, as are most products of nature. Three dominant patterns will be described—straight, meandering, and braided—and, as much as known, their causative processes. Straight channels generally offer least problems for land management, but unfortunately, they are the exception. The rule is the meandering channel. Channel alignment changes offer relatively quick and drastic adjustments to a new situation and are easily recognizable indicators of past, present, and possibly future channel developments.

Generally, channel shapes respond quickly to changes in the fluvial system because shape influences water as well as sediment transport. Thus, channels closest to a semicircular shape are most efficient for conveyance of water and fine sediment. Coarse sediment requires relatively wide, shallow channels (Leopold and Maddock 1953). Unstable channels may therefore be recognized by channel shape changes. Parameters have been developed which permit quantitative determination of these changes.

Consistency of bank material and availability of bank vegetation exert a strong influence on channel shape. Besides these factors, water movement within or over banks may play an important role in the attainment of bank stability and shape. But bank characteristics also influence channel patterns. For example, banks of cohesive material (clay and silt, mainly) usually preclude braided stream patterns, but noncohesive materials favor them. Bank characteristics may change due to lateral stream movements. Recognition of these changes is important because they may indicate future bank stability conditions and channel shape. Banks are therefore considered separately from shape.

Older geologic literature overemphasized the importance of the profile in channel adjustment. As shown by the preceding section and stated by Wolman (1955), slope is not necessarily the primary mechanism by which equilibrium is maintained.

Three major processes lead directly to adjustment of the longitudinal profile: (1) aggradation, (2) degradation, and (3) armoring. These processes act on the topography and the material in bed and banks. General relationships between profile, topography, and geology can be utilized to human advantage. An example is the use of a bedrock outcrop for gradient stabilization instead of a check dam.

Generally, aggradation and degradation processes are undesirable, but necessary, adjustments where there are drastic differences between the sediment-carrying capacity of a flow and the sediment load coming into a channel reach. Aggradation may lead to channel widening and flooding; degradation to bank caving and lowering of the water table in areas close to the channel. Armoring can stop the degradation process if sufficiently large bed material is available. In this sense, armoring is a beneficial byproduct of degradation. Amount and depth of the armor material below channel bottom determine the depth of degradation before an effective armor is established.

Processes Affecting Channel Pattern and Shape

Bar Formations

Bars are defined as bed forms having lengths of the same order as the channel width or greater, and heights comparable to the mean depth of the generating flow (American Society of Civil Engineers 1966). Bars are deposits that may be visible or submerged, and of grain sizes ranging from clay to boulders. Most are built predominantly from sand or gravel or both. In longitudinal section, bars are approximately triangular. The upstream slopes are very long and gentle, while the downstream slopes are short and approximately the angle of repose of the bed material. Since bars are an active part of the geometry of flow, they change in size, height, or location with flow conditions.

Generally, bar surfaces rise and fall with the magnitude of flow. Bars generated by high flows frequently appear as small islands during low flows. On sandbars, portions of the upstream slopes are often covered with ripples or dunes.

Bars may be classified as point, alternating, transverse, middle, or tributary bars. The most obvious one may be the point bar, which develops near the convex (inside) bank of channel bends (fig. 6). Its shape may vary with changing flow conditions, but it does not move relative to the bend. The processes leading to this bar formation demonstrate the strong relationship between flow and bed forms. Rzhanitsyn (1960) describing the processes in bends, stresses not only the longitudinal currents but also the cross currents that influence the channel-forming processes. The actions of both lead toward the development of a deep pool at the concave (outside) bank and a bar at the convex bank (fig. 7).

Two causes were thought to be responsible for the transverse circulation: the centrifugal force acting on the particles passing the curve and the difference in the longitudinal component resulting in a general spiral-like motion. The secondary circulation, sometimes also called helical, helicoidal, or spiral flow or current, continually sweeps sediment from the pool depression toward the convex bank, bringing clearer water from the upper layers to the bottom and thus increasing the erosional activity. Most of the material eroded from the pool is deposited on the point bar. These processes lead to asymmetrical cross sections in

bends. Upstream and downstream ends of the bar are pointed. Intensity of erosion increases with increasing secondary circulation. Since this circulation increases with decreasing radius of curvature, the depth of the pool is inversely related to the radius of curvature of the bend. Therefore, gentle bends will have shallower pools than sharp bends (fig. 7).

The maximum depth at the concave bank is greater than that of the straight reach. With the deepening of the channel at the concave bank and the reduction of depth at the convex bank, the principal flow gradually moves closer to the concave bank. There the longitudinal velocity of flow increases due to greater depth. In contrast, the longitudinal velocity at the convex bank is reduced with decrease of depth.

High flows tend to shorten the thalweg (i.e., the flow selects the shortest route as it cuts across the point bar). This process leads to erosion at that part of the point bar located toward the center of the channel. The bar becomes narrower (fig. 6) until other flows may build it up again. Point bars can also be fully submerged resulting in loss of bar height, or a high-flow channel may be cut through the point bar (fig. 8).

Although helical flow apparently plays an important role in the process of erosion and deposition in a bend, the mechanics of bend formation are not known. Meanders are known to form on the surface of glaciers where they are cut by meltwater carrying no sediment load, and point bars do not form. Meanders are also known to exist in ocean currents such as the Gulf Stream where boundaries and loads are absent. Leopold and Wolman (1960) argued, therefore, that the shapes of curves in streams are primarily determined by the dynamics of flow rather than by the sediment

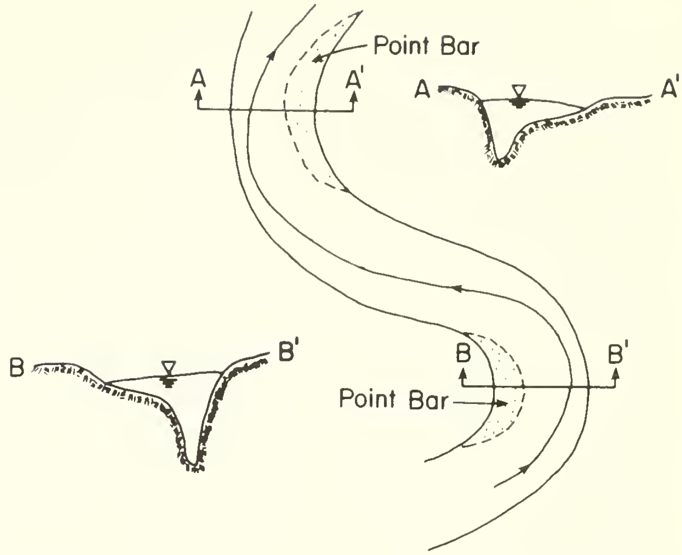


Figure 7.—Schematic presentation of channel shapes in gentle (A-A′) and sharp bends B-B′). The line in the channel of the plan view represents the thalweg. Note in the section view the increase of pool depth with decreasing radius of curvature and the higher water surface elevation at the outside as compared with the inside bank. This is due to the gravitational force and is called superelevation.

they carry. These authors compiled evidence that when other conditions, as yet unknown, cause a stream of any size flowing in a deformable channel to develop a meander pattern, the radius of curvature will be between two and three times the mean channel width.

In contrast to point bars, alternating bars are not stationary. While point bars form in channel bends,

Figure 6.—Point bar in Salt River north of Phoenix, Ariz. Flow is from left to right in the foreground. Note the pointed downstream bar end.

Figure 8.—In Black Canyon Creek, northern Arizona, high flows cut a channel behind this point bar to speed up water conveyance through this stream reach. Flow is from left to right.

alternating bars develop in straight channel reaches, and are the reason why natural streams rarely remain straight. They "tend to be distributed periodically along a channel, with alternate bars near opposite channel banks. Their lateral extent is significantly less than the channel width. Alternating bars move slowly downstream" (American Society of Civil Engineers 1966). The thalweg meanders between these bars, creating an undulating profile by forming pools and riffles (figs. 9 and 10).

Alternating bars may not be visible because they are often partially submerged. Pools and riffles are spaced more or less regularly at a repeating distance equal to five to seven widths of the channel (Leopold et al. 1964). Because the spacing is similar to that of bends in meandering streams, these authors suggest the pool-and-riffle mechanism in straight channels is the same as that creating meandering channels, possibly associated with some wave phenomenon. Normally, the bed material on the riffles tends to be somewhat larger than in the pools, but at high flows, the reverse may exist.

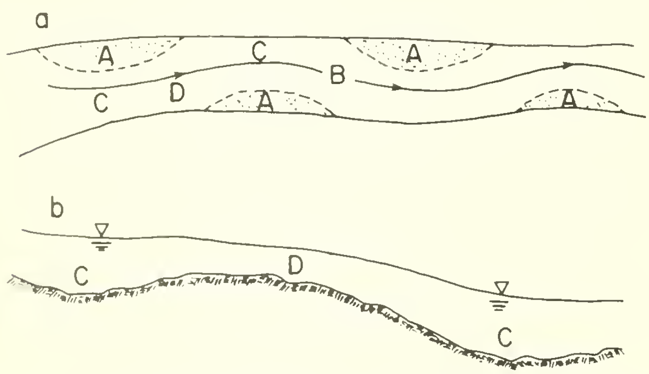


Figure 9.—(a) Schematic plan view of alternating bars (A) and thalweg (B) in a straight channel reach, and section view of the associated longitudinal profile (b) showing pool (C) and riffle formations (D). Riffles form at crossings of the thalweg between bends.

Alternating pools and riffles were not found in high mountain streams of the Sangre de Christos, New Mexico (Miller 1958), nor the Rocky Mountains, Colorado, or the White Mountains, Arizona (Heede 1975). Miller argued the coarse material, left by Pleistocene glaciers or deposited by steep cliffs, etc., is too large to be effectively transported by the present-day flow regime. In Heede's streams, gravel bars were not spaced at a repeating distance, but distance decreased with increasing channel gradient (fig. 11).

Heede's gravel bars could adjust their height with flow while remaining stationary; transverse bars of rivers move slowly downstream and occur both as isolated and as periodic forms along a channel. Generally, they occupy nearly full channel width (fig. 12). Transverse bars result from slope adjustment processes. Their main effect on the flow is increased bed roughness, as shown by strong relationships between bed form and resistance to flow (Simons and Richardson 1966).

Where the width-depth ratio is very large and the stream divides itself into two or several branches to adjust for lost depth, middle bars will be created. At times, they appear as submerged islands. Some are sufficiently long to bear willows (fig. 13). Middle bars are a typical bed form for braiding streams, characterized by extremely wide and shallow channels and flows

passing through a number of small, interlaced channels separated by bars (Friedkin 1945).

Tributary bars often form immediately downstream from tributary junctions (fig. 14). They indicate large sediment discharge from the tributary stream. At times, this discharge may outweigh the capability of the main stream to transport the additional load. A sediment fan may be built at the tributary mouth into the main stream (fig. 5). During a subsequent large flow of the main-stem river, the sediment fan may be fully or partially removed, and only a tributary bar may remain.

Bars are an integral part of the hydraulic geometry of a stream. With the diminution or exhaustion of flood plains and river terraces by gravel quarrying, the streams themselves become increasingly attractive gravel sources (fig. 15). If bars are destroyed by natural adjustment processes, they will not form again unless the hydraulic geometry changes back to the original condition. In contrast, bars obliterated by man will be reestablished if a sufficient sediment supply is available. If not, or if reestablishment is very slow, adjustments such as degradation may take place. Degradation is generally detrimental to the environment. Where transverse bars (bed forms created for slope adjustment) are removed, bedscarps will soon signify degradation is taking place. Removal of sediment will invariably destroy the bed armor, and a new armor can only be established by lowering the bed, which often leads to bank instability.

Figure 10.—Alternating bars (arrows) in Black Canyon Creek. High flows cut small channels through the bars. Flow is toward background.

Figure 11.—Looking upstream on a transverse gravel bar (between arrows) in a small mountain stream (North Fork of Thomas Creek, Arizona White Mountains). Note the steep slope gradient (average 17%) that required adjustment of slope. Consequently, several transverse bars developed above the indicated bar.

Gravel operations may not be harmful where large sediment loads are available to replace bars quickly, thus avoiding drastic upsets of the stream system. The Eel River in California, one of the largest known sediment carriers in the United States, may be such a stream. But even in this case, we would not know the long-term environmental effects (redwood trees have lived for more than a thousand years on the periodically aggrading Eel River flood plain, as shown by multilayered root systems (Stone et al. 1972)).

Channel Patterns

In light of the interdependency of many hydraulic variables, it is not surprising to find a large variety of

Figure 12.—Downstream view of a transverse bar (between arrows) in the Verde River, Arizona. The bar is not fully exposed across the channel. Darkness of the water surface in the two bar openings (A and B) suggests submergence of the bar at these locations. Sediment accumulations above this bar, a natural slope adjustment structure, are indicated by shallow flow depth in the foreground.

Figure 13.—Middle bars (arrows) in the Salt River near Roosevelt Reservoir bear vegetation such as willow and saltcedar. Flow is from left to right. At high water stages, the bars are submerged, while at lower stages, shown in figure, stream braiding develops.

Figure 14.—Where the Salt River (a) is joined by tributary Verde River (b), a tributary bar (c) has formed. Size of tributary bars changes readily if sediment loads delivered by the tributary fluctuate strongly. The submerged outline of the bar at (c) suggests exposed bar size was reduced considerably by recession flows after the heavy load-carrying floods of 1978 and January 1979.

Figure 15.—Many rivers have a substantial supply of aggregates, demonstrated by a large middle bar in the Verde River, central Arizona, that may be sought by industry. In many situations, however, removal of such material would detrimentally affect stream equilibrium.

channel patterns because pattern changes are one possibility for adjustment of the hydraulic geometry to a new situation. This is especially true if the slope must change. The large variety of patterns can be reduced to three basic types: straight, meandering, and braiding. There are, of course, intermediate forms.

Long reaches of straight channels are hard to find in nature. Even in straight channels, the thalweg wanders back and forth between the banks (fig. 10), and only the high flow may fill the straight reach. One could thus conclude that meandering and braiding channels offer better and easier ways for attaining equilibrium conditions than straight channels. Meandering and braiding increase the length of the thalweg and thus decrease slope. A measure of meander intensity is sinuosity, expressed as the coefficient of thalweg length divided by valley length. Large coefficients, therefore, express strong sinuosity (meandering). A straight reach would have a coefficient of 1.

In braided streams, the flow is relatively shallow and the width-depth ratio large, larger than in meandering streams. The stream flows around many islands (fig. 16). If this process increases, branching of the main channel may occur, the flow running in different channels more or less parallel to each other, joining and anabranching (diverging) in succession. Brice (1975) called these "anabranching streams."

Why channel patterns change cannot be precisely answered yet. Certainly, localized channel width increases may lead to meandering because of introduced flow deflections. A large boulder or other obstruction, for example, may cause a local channel width increase that results in a meander. But on glaciers meanders also appear without visible flow deflections.

Profile is one of the major causes for pattern changes. Braided streams are steeper than meandering streams. Steeper streams have higher velocities, attack banks more strongly, and carry larger sediment loads.

For bank erosion to occur, erodible bank material must be available. For example, braiding does not usually take place where banks are densely vegetated, but may where this cover is sparse. Although cause and effect are suggestive, they are not proven (Leopold et al. 1964).

In alluvial streams, whose bed and banks are formed by sediment transported by them, amount and character of the particles composing the sediment load also seem to have an important effect on channel pattern. It appears available load is one of the factors separating meandering from braided streams. Lane (1957) concluded not only overloading by sediment but also steep slopes are prerequisite for braiding. Overloading leads to aggradation, causing wide channels where banks are soft and, thus, the development of bars and islands. The width-depth ratio is larger than in meandering streams. But Leopold et al. (1964) pointed out that braiding is not necessarily associated with aggradation, since it can represent the equilibrium pattern (sediment inflow equals sediment outflow). Yet it can be argued that for braiding to occur depositions (aggradation) are required to initiate drastic channel width increases; with braiding, a new equilibrium condition may be established.

In flume experiments, Shen and Vedula (1969) showed depth of flow may become so shallow due to sediment overloading that flow could not occur in a single channel. It had to divide into several narrow channels to increase depth of flow and sediment-carrying capacity.

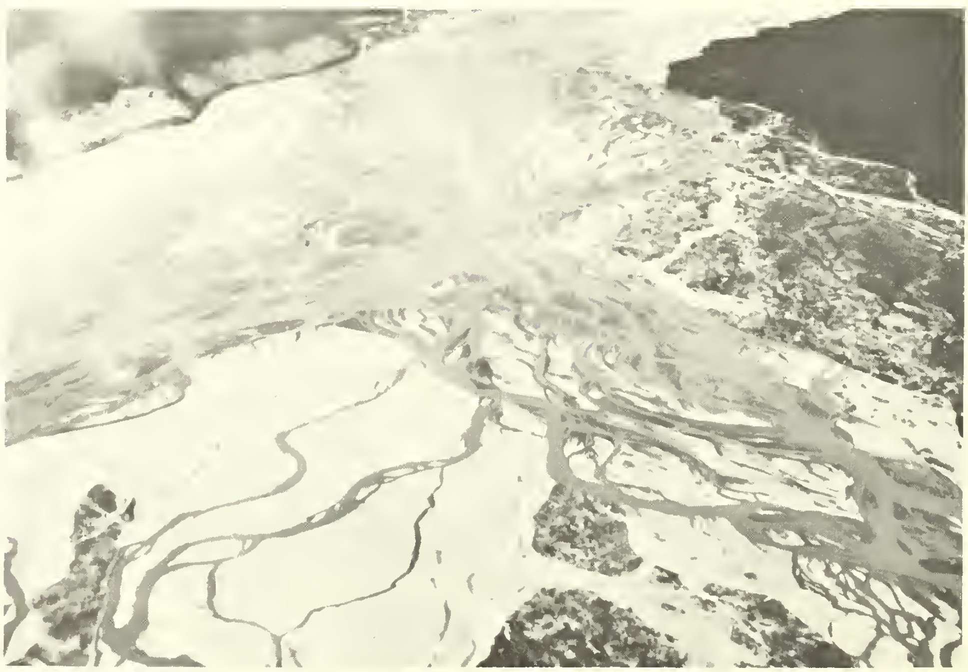


Figure 16.—Looking downstream on Delta River, a braided glacial stream draining the north face of the Alaska Range in central Alaska. Glacial streams tend to develop very pronounced braided patterns. (Courtesy Troy L. Péwé, Arizona State University)

Figure 17.—Heavy sediment loads in this Salt River reach above Roosevelt Reservoir, Arizona, created a wide bed with shallow flow depth. Thus, stream competence (sediment-carrying capacity) was drastically reduced. To increase flow depth (and competence), the flow split into several channels (arrows). Flow in the foreground is from left to right.

That this process takes place also in rivers was demonstrated during a recent recession stage of the Salt River, Arizona (fig. 17).

In a glacial stream on Mount Rainier, Washington, Fahnestock (1963) observed braiding at much greater magnitude when an abundant bedload was introduced than when the material was derived just from bank erosion. Fluctuating flow discharges also favored braiding.

In some situations such as mountain streams flowing in V-shaped valley bottoms, lateral stream movements are not possible. A straight channel reach may therefore remain straight. Slope adjustment is possible only within the given channel. In small streams, this adjustment may be achieved by the formation of transverse gravel bars (fig. 11) and incorporation of fallen trees and logs (Heede 1975). Apparently, slope is seldom adjusted by severe degradation because of the presence of large bed material sizes.

The limitations set by the topography, such as V-shaped valleys, help to explain why braids tend to develop in channels having certain variable combinations, while meanders occur in different conditions; the straight pattern can occur in either.

Although causes for pattern changes cannot be precisely delineated (Morisawa 1968), channel changes obviously take place in response to changed stream conditions. For the land manager, meander and braiding processes are usually costly because valuable land may erode or other investments, such as roads or buildings, may be destroyed. It is therefore desirable to control lateral stream movement, but vertical bed adjustment processes may be initiated if the lateral process is stopped. Unless durable bed armor prevents channel depth changes or these changes are acceptable, additional bed control measures will be required. If depth changes are permissible, it should be recognized bed adjustment will also take place in the tributary streams. Thus a stream control measure may have adverse effects far beyond the immediate region of the stream.

As a general rule, the land manager should live with the present natural adjustment processes and, if possible, offset losses with land improvements elsewhere.

Channel Shapes

Channel shape is of management interest because shape is predominantly influenced by the (1) quantity of water; (2) the type of sediment load (suspended load, the material moving in suspension; or bedload, the coarse material moving on or near the bed); and (3) the type of bank material. Any change in one or more of these factors will therefore introduce a shape change as well. Recognition of shape changes is a first step in the determination of their cause, but recognition is not always easy because of turbidity of the water, or transitional shape changes that are not easily seen (for instance, from slightly parabolic to rectangular). For these cases, the width-depth ratio and the shape factor can be calculated from field survey notes on channel cross sections. Both will be described in succeeding sections.

Land management measures can influence water and sediment discharge. Costly stream training measures such as riprap or gabions change banks and

their material makeup. Such changes may be beneficial or detrimental to management goals. For example, a semicircular cross section, not existing in natural streams, would convey the largest quantity of water with the least resistance (erosion or deposition). The more channels deviate from this idealistic shape, the less water will be conveyed, and flow resistance increases. Thus a wide flat channel will show tendencies for aggradation by sediment, possibly leading to a braided channel pattern. Obviously, granting permission for additional water conveyance through such a channel would add to the problem.

Relations between shape and sediment load show channel width increases with increasing coarseness of the sediment particles. Thus, causes for channel widening may be traced back to new sediment sources on the watershed caused by events such as landslides or rockfalls from talus (cliff debris) slopes, or channel deepening in an upstream reach may make available coarser material. Of course, the basic question of what caused slides or deep cutting must still be answered before corrective management actions can be initiated.

Also, the particle sizes in the channel banks determine channel shape. While banks with a high silt-clay percentage lead to narrow and deep channels, those with a predominance of sand and coarser material develop into wide, flat channels. Thus, lateral stream movements may lead to shape changes by exposing different bank materials.

Lateral stream movement may not be caused by management but may result from natural adjustment processes where dynamic equilibrium was lost due to unusual events such as earthquakes or land flows (unusually large land slides). If bank material changes are detected at an early stage and future problems are expected, protective actions could be taken in time. For such a decision, projections must be made as to other types of adjustment the stream may undergo if lateral movement is stopped. Down cutting may take place, for example, requiring additional bed control structures under expected severe conditions.

Width-depth ratio.—The width-depth ratio relates the top width (W) of the channel to the mean depth (d). Mean depth is defined as the cross sectional area at bank-full stage divided by the top width. Where bank-full stage would not be a meaningful criterion, channel width and flow depth should be taken at high water mark. In cross sections with nongeometric forms, a planimeter or similar instrument is best suited for determining cross-sectional area.

In cross sections with pure geometric shapes, the following relationships hold: in a triangular channel, the width-depth ratio remains constant with changing discharge; the width-depth ratio decreases in trapezoidal and elliptical cross sections when discharge increases; and width-depth ratio decreases much more rapidly with increasing discharge in rectangular channels.

Width-depth ratio changes with discharge can be graphically shown if the ratio is expressed as a simple power function of discharge:

$$w/d = rQ^s$$

where Q is the discharge, and r and s are numerical coefficients. The value of s, the slope of the line resulting from a log-log plot of the equation, expresses the relative rate of decrease of the ratio with increasing discharge (i.e., it constitutes a measure of how readily a stream adjusts width and depth to discharge changes). An example from three stations is plotted in figure 18.

In general, cross sections in straight reaches have a large width-depth ratio. In bends, this ratio is small. The sharper the bend, the deeper the pool, and the smaller the ratio (fig. 7). This relationship is so strong the cross-sectional shape of the pool could be used to determine the approximate degree of curvature of the bend if empirical data on bends and bank material are available.

Schumm (1960) found that in western channels the type of material in banks and bottoms controls the cross-sectional channel shape. When the mechanical analysis of the soils was related to the width-depth ratio, linear regression indicated that increases in the ratio conformed with the increases of the average percent sand in the measured load: wide, shallow channels form in sandy soils, while clayey soils lead to narrow, deep channels.

An extremely large width-depth ratio for a given river would indicate braiding must be expected because of large available loads and unstable banks or very large width of channel. The decreased flow will concentrate into smaller branches to obtain some depth and velocity for the transport of the material. Values for the ratio should be evaluated relative to prevailing values within the stream system. The range of the ratio can be large. Fahnestock (1963) found values ranging from 10 to 71 for glacial streams of Mount Rainier in Washington, while those for small streams in the southern Rocky Mountains of Colorado ranged between 3 and 27 (Heede 1972).

Shape factor.—The shape factor is the quotient of maximum depth divided by mean depth. Because the value may be the same for a variety of unusual cross sections, the factor must be interpreted cautiously. Only in exceptional cases, however, do channels in alluvial material have unusual sections. If considered as geometric figures, a triangular channel has a shape factor of 2, a parabolic section 1.5, and a rectangular section 1.0.

As stated before, the semicircular channel would have the most efficient cross section, because for a given cross-sectional area it has the smallest wetted perimeter. If slope and roughness are constant, the velocity increases with the hydraulic radius, which is the coefficient of area of flow over wetted perimeter. Hence, the semicircular channel would discharge more

water than any other channel shape. The most efficient naturally occurring cross section is a parabolic channel with a shape factor of 1.5. Thus, the discharge efficiency of a channel can be quantitatively judged. This may be of importance for projects which require additional conveyance of water. Where cross sections appear to be obscure, plotting the section will reveal if the factor truly expresses the shape. In the streams mentioned above, Fahnestock's (1963) shape factors ranged from 1.1 to 2.7 and Heede's (1972) ranged from 1.1 to 2.3.

Avoiding pitfalls in "in-stream flow" investigations.— Surveys of channel cross sections are an integral part of the land manager's "in-stream flow" investigations. The present type of flow should be defined because, as shown in a previous section, with flow the thalweg may

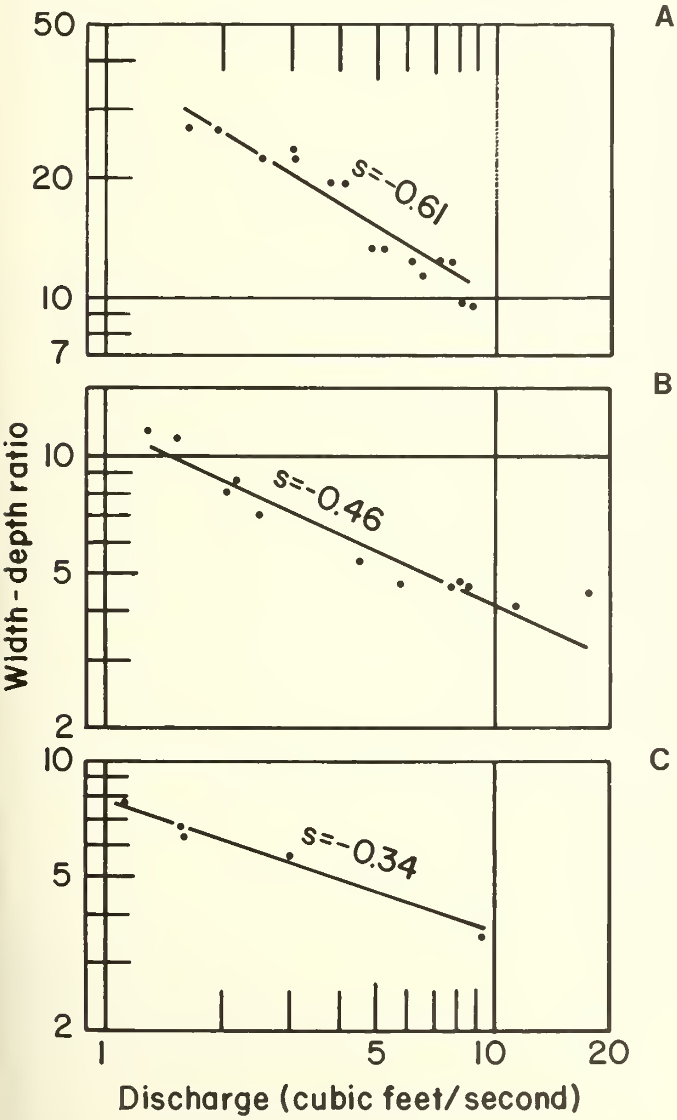


Figure 18.—Relationship of width-depth ratio to discharge for three stream stations of Fool Creek, central Rocky Mountains in Colorado. Station A adjusted most quickly to discharge changes (sediment carrying capacity is better maintained in A than in B or C).

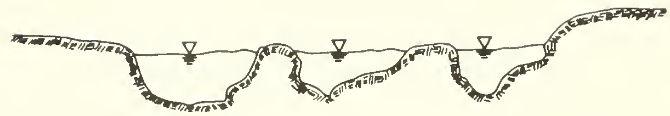


Figure 19.—Schematic diagram of a channel cross section in an anabranching river. The overall appearance suggests several independent parallel streams.

change its position and in turn channel shape. At low flow, for example, the stream may create a pool at a bank due to increased flow sinuosity; while at high flow, water fills the channel and a low occurs in the section center.

How flow types can influence channel shapes is determined not only by the thalweg position in the cross section, but also by changes of the stream power. The cross sectional channel shape is directly related to the changes of the stream power τV across the stream, where τ is the tractive force γRS; γ represents the specific weight of water, R is the hydraulic radius A/p, A represents the area of flow, p is the wetted perimeter, and S is the slope. The wetted perimeter is that part of the channel cross section submerged under the water of a given flow. Simons and Richardson (1966) have shown τV is related to mean sediment grain size, which determines bedform and, in turn, resistance to flow.

Cross sections can be influenced also by channel patterns. Thus a straight reach tends to have a V-shaped cross section; in bends, a pool exists at the outside bank (fig. 7); while in braided streams the cross section has an undulating outline. Where anabranching takes place, a given stream location may have a succession of channel cross sections each separated from the next by unchannelized sections (fig. 19). The survey should therefore include information on the channel pattern and the location of the section relative to pattern features such as "at crossover between meanders." This information is important because the pattern itself may be responsible for a given type of flow and channel shape, and different processes induced by different patterns may form similar cross sectional shapes. Examples will illustrate this.

In a straight reach, two circulation cells have been observed in the plane perpendicular to the flow (Leopold et al. 1964). The authors presented cross-channel water-surface profiles showing a marked central hump and water surface elevations lower at the two edges of the stream, resulting from the transverse water circulations (fig. 20). This so-called secondary circulation moves from the edges to the stream center and then downward. There may also be several circulations above each other, but circulation seems to take place in an even number of cells (Koloseus 1971). The secondary circulation has been associated with

turbulent flow in prismatic channels illustrating an influence of channel shape on flow characteristics.

At a meander crossing (the point of inflection from one meander to the next), the flow is often deflected towards one bank. This leads to the formation of a pool there and a bar at the opposite bank. Appearance of such a section in a cross-sectional drawing may be similar to that of a meander. Only the plane view would show dissimilarity in appearance.

If instability of flow increases at a meander crossing, a bar may form in the middle of the channel, practically dividing the flow into two branches. At low flow, this may appear like the cross section of a braiding stream. Description of the section location is therefore required. Because of inherent instability, meander crossings should be avoided for structural installations such as bridges and culverts.

Channel Banks

With time, most natural channels form their bed and are therefore embedded in alluvial materials. Banks may offer serious soil mechanical and fluvial geomorphologic problems. Factors such as temperature, chemistry of clay, or vegetation influence bank stability. Bank material may range in size from clay to boulders, and the occurrence of this material may change with location or it may be stratified. Generally, banks with high clay content are more stable than those without clay. Therefore, the bank material must be considered if bank stability is evaluated.

Failures of banks are customarily classified into slip failure and scaling. Scaling is a type of exfoliation that produces thin flakes, laminae, or scales. Slip failures are induced by piping (development of pipe-like subterranean tunnels) or often indirectly by horizontal stratification of the bank materials. Scaling begins in smaller magnitudes at the bank toe, generally, and proceeds up the bank.

Where piping takes place, material stratification may add to the problem. This stratification should be considered relative to high and low flows and to the elevation of the water table in the bank. Piping is subterranean erosion where soil is removed from root canals, cracks, burrows, or other voids in the solum. Normally, pipes have an inlet and outlet, the latter at a lower elevation, and thus convey overland flow. Repeated flows increase tunnel size until it collapses.

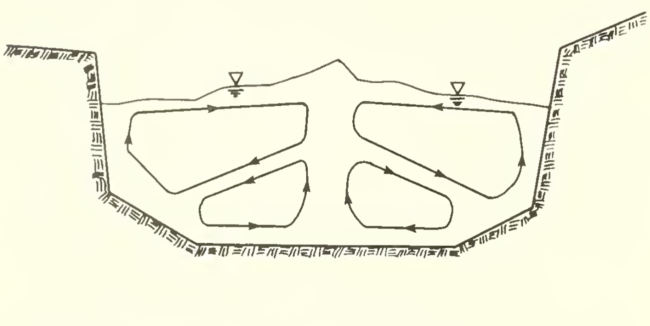


Figure 20.—Idealized secondary circulation cells in a cross section of a straight reach. Water surface elevation shown (Leopold et al. 1964). Note the water surface shows a hump in the channel center and a low at both banks. The central hump may be as much as 1 foot above water surface at banks.

Heede (1971) described soil piping in gully banks with high-clay soils (>45% clay), and found piping was related to high exchangeable sodium percentage, low gypsum content, and fine-textured soils with montmorillonite clay.

Vegetation as a bank stability factor must be evaluated in terms of plant vigor, density, and rooting depth. Obviously, the stronger these characteristics, the greater the impact on bank stability. Research results are few on this subject, and the designer can be guided only by experience and judgment.

Where the load of a stream consists of large amounts of fine sediment, extensive berms may form along the banks by deposition of silts and clays. On the other hand, where channels widen continuously, the process must be suspected to be a function of the bank material.

Processes Affecting Longitudinal Profile

Longitudinal Profile Relationships

The longitudinal profile of a stream is determined largely by the topography. In general, stream gradients will decrease from the headwater downstream to the mouth, but gradient steepening or lowering may occur in any stream reach, especially if there are human or natural controls such as rock outcrops or rock type changes. When evaluating the overall shape of the longitudinal profile, one must be aware of the scale factor that may enhance local irregularities and thus misconstrue the overall shape. Profile shapes can be classed as concave, straight, or convex if local irregularities caused by bed features such as bars, pools, and riffles are ignored.

The longitudinal profile is a function of the following variables: discharge, load, size of sediment particles, flow resistance, velocity, width, depth, and slope. Since there are more unknowns than equations, an exact solution incorporating all variables is not possible. Simplified equations of various forms have been devised, however, typified by two kinds. One is based on Sternberg's (1875) abrasion law, the other on Gilbert's (1880) law of declivities.

Langbein (1964) suggested the concavity of river profiles with uniform discharge increases with length and decreases with rate of discharge. He proposed further that profile shape is independent of base level and is determined by length, fall, and discharge. Concavity can be expressed as the ratio $2A'/H$, where A' is the difference in elevation between the profile at mid-distance and the straight line connecting the ends of the profile, and H is the total fall (fig. 21).

In small mountain watersheds with homogeneous geology, Heede (1977) found ephemeral streams with convex profiles, while perennial streams showed con-

cave profiles. He argued, considering homogeneous geology and other parameters of flow and channel geometry, concavity represents the equilibrium profile and convexity represents the profile of streams outside of equilibrium.

Previous sections showed that the processes leading to a given profile are interrelated with others. Together, the processes tend to either establish or maintain equilibrium conditions. Since the profile directly influences flow velocities, artificial changes of the equilibrium slope should be avoided.

Where a stream must share a narrow valley bottom with a road, the stream reach is often shortened, steepening the channel slope. Normally, a bedscarp develops at the downstream end of the shortened reach and proceeds upstream with time, deepening the channel (fig. 22) and the tributaries. The deepening of the main channel lowers the local base level of tributaries to which they must adjust. In many cases, available space does not permit relocating the road in such a way that new channel length equals the original. Artificial armor plating or check dams would solve the problem, but are expensive. Where check dams are used, it is important that the last upstream structure will not create a pronounced break in gradient at the upstream toe of the future dam deposits. A smooth transition from the lower to the upper gradient is required to avoid the development of a bedscarp at the deposition toe. An expected deposition gradient should be estimated from measurements of deposits above artificial barriers within the stream system.

Aggradation

If the sediment inflow into a reach is in excess of the reach's carrying capacity, the excess material is deposited until a new slope is established that equals the upstream slope. This is the new equilibrium slope. Based on flume experiments, Suryanarayana (1969) reported on the mechanics of aggradation. The new equilibrium slope established by aggradation can carry all the incoming sediment, but downstream the slope has not adjusted yet and deposition occurs. This obstructs the flow, and deposition occurs above also. Thus, deposition takes place above and below this

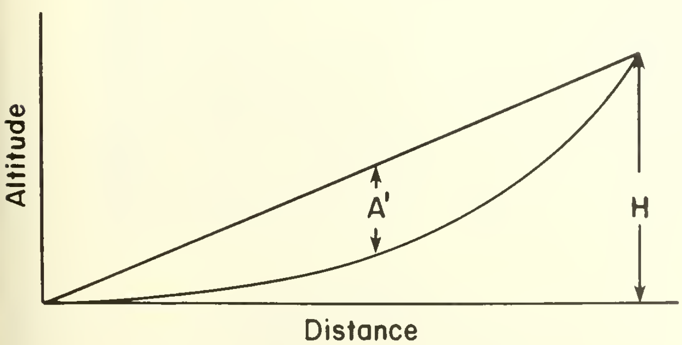


Figure 21.—Schematic illustration of Langbein's (1954) profile concavity ratio.

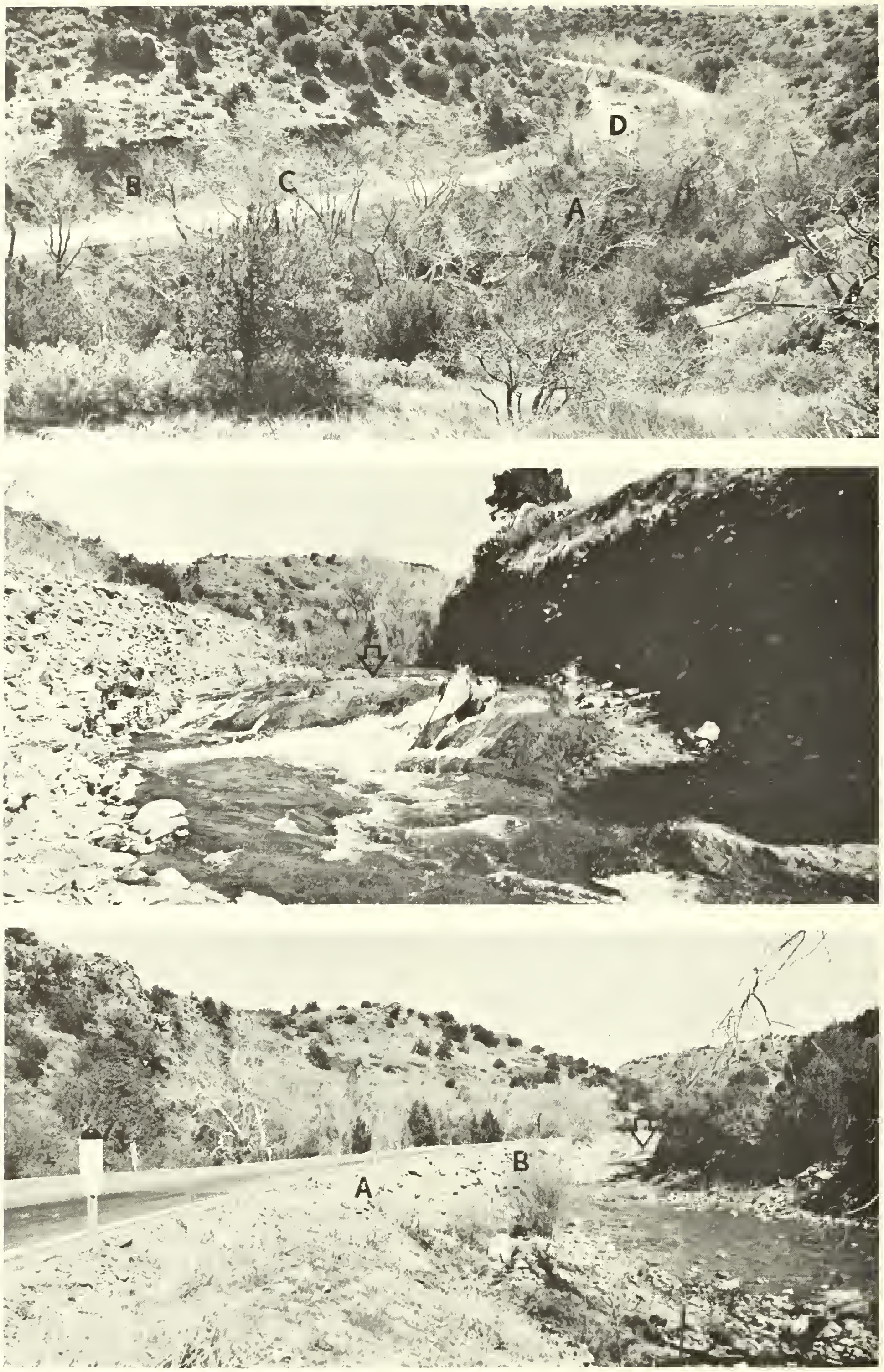
location, raising the bed parallel to the new equilibrium slope. The rate of this movement decreases with time or with downstream advance, and so does the rate of aggradation. The channel upstream and downstream from the aggrading front behave as two different reaches with different flow conditions. Aggradation ceases once all slope segments allow equilibrium sediment discharge.

Aggradation creates a slightly convex longitudinal profile (Suryanarayana 1969) resulting from interaction between transport and deposition. Since more power is required to move coarse material than fine material, the coarser sediment will be deposited first while the fines move farther downstream. Particle sizes of sediment therefore decrease downstream within the aggrading reach. Particle abrasion becomes an additional factor (Schumm and Stevens 1973).

Where aggradation takes place, the streambed rises slowly and, with time, the tendency increases for the flow to spill over the banks. This will lead to rising of the banks. A good example is the Rio Grande at Albuquerque, N. Mex., where the streambed aggraded to an elevation 4 to 6 feet above the river's flood plain. The banks rose, but not high enough to contain exceptional floods and stream training measures were required to safeguard the city.

The process leading to natural levee formation (raised banks) can be explained by sedimentation. When floodwaters spill over banks, a sudden loss of transporting power occurs at the brink of the banks due to decreasing flow depth and flow velocity. Most of the transported sediment is thus deposited at the brink and much less material is available for deposition on the flood plain (fig. 23). Under extreme flooding or bed aggradation, the stream may divide itself by building another channel on the flood-plain side of the levee, and the levee keeps both channels apart. This process may continue during successive floods, and the end result is a "braided" river. This example illustrates an important fact in stream hydraulics: different types of processes may lead to similar end results.

Unfortunately, flume studies are not helpful in predicting the behavior of natural alluvial channels. The main reasons are flumes have rigid boundaries, and sediment characteristics such as shape and smoothness cannot be modeled. Knowledge of natural streams must therefore be developed under field conditions. Yet, due to the intricacy of different adjustment processes in alluvial channels all of which may be acting at one time, we cannot precisely forecast what will happen at any one point. The problem is compounded by the fact individual processes require different time scales. Thus, bed forms may adjust quickly and width slowly or erratically, while the processes leading to longitudinal stream profile changes are slow. The aggradation process is somewhat faster than degradation; the two processes generally alternate along the length of the stream. In short, morphologic adjustment processes are stochastic in nature, and stream behavior prediction is therefore a probabilistic problem.



a

b

c

Figure 22.—(a) In mountain country, highway construction often infringes on streams. A relatively large meander bend (A) of Sycamore Creek, central Arizona (flowing from left to right), was cut off and the streambed relocated to the opposite side of the road (B). Thus streamlength was shortened, slope gradient steepened, and a nickpoint introduced at (D) that led to the development of a bedscarp in the volcanic bed rocks. This scarp advanced about 300 feet upstream (C) within approximately 25 years. At (D), the original meander bend connected with a short straight reach still used by the creek. (b) Closeup view of the 8-foot-deep bedscarp (arrow). Adjustment processes not only caused a bedscarp but also tried to reestablish the meander, endangering the road bed by undercutting. (c) Rock riprap bank protection was required between A and B to protect the road. Arrow signifies bedscarp location.

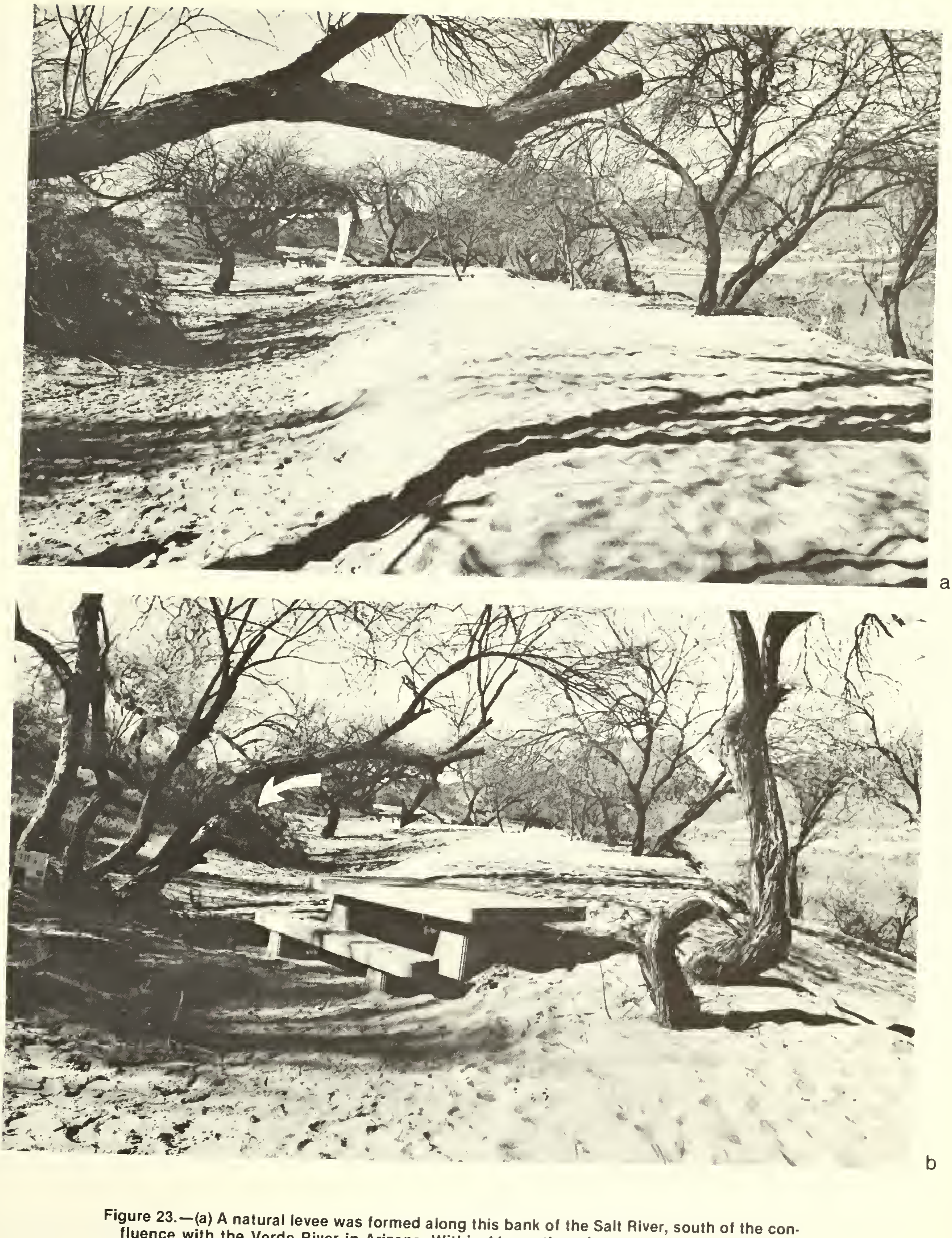


Figure 23.—(a) A natural levee was formed along this bank of the Salt River, south of the confluence with the Verde River in Arizona. Within 11 months prior to the date of the photograph, three major floods had covered the picnic area indicated by a partially buried table (arrow). Note the cross-sectional dike shape of the levee. The view is downstream. (b) The levee partially buried one picnic table (foreground) and one fully (black arrow). White arrow points to the high-water mark of the January 1979 flood.

Unless an unusual event occurs such as a flood, slow profile adjustments are difficult to observe. Normally, many years of investigation will be required, therefore, to test the effectiveness of a design. Observation reaches should be as long and as uniform as possible so that the average bed conditions are insensitive to seasonal changes (Gessler 1971) that could distort the results.

Degradation

In general, degradation processes are extremely slow, especially where geologic processes such as uplift are involved. A classic example is the Grand Canyon in Arizona.

Where equilibrium conditions have been violently disturbed (massive land slides, earthquakes), degradation may be fast initially, but will become progressively slower with time. An example is Manti Creek, draining the Wasatch monocline in Utah. In 1974, the third largest modern landflow in the United States lifted portions of the streambed by about 110 feet. Within 2 to 3 years, degradation in the uplifted reach amounted to about 60 feet. Degradation is now so slow that downcutting rates cannot yet be established.[2] Manti Creek's behavior, typical for alluvial streams, illustrates that degradation processes are asymptotic in nature and, therefore, slow if considered over the full adjustment time.

The profile of a degrading bed is concave (Suryanarayana 1969), and the associated channel cross sections tend to be V-shaped (Gessler 1971). As for aggradation, the processes shaping the profile of degrading reaches can be described in terms of sediment transport. During degradation, material is picked up from the bed until load limits (threshold values for the transport of particular grain size) are reached. While certain smaller sizes are still set in motion, the larger ones remain in place until even the small sizes cannot be picked up. With the limitation in bed particle movement, the slope of the concave profile decreases downstream. The gentler bed gradient will have an equilibrium sediment transport rate less than that of the upstream degrading reach.

The tendency for formation of V-shaped cross sections in degrading channels is a result of variations in resistance to flow across the channel. Normally, carrying capacity for sediment is lower near banks than in the channel center due to bank roughness. Pickup of bed material may therefore increase toward the center. Other processes, however, such as spiral-like flow in bends (discussed in an earlier section) may have an overriding influence on channel cross-sectional shape. Also, the profile may not be concave if only considered over short distances.

The processes of degradation as well as aggradation are thus correlated with flow and sediment transport. The aim of these processes is to adjust to some change in the stream system; the end result is a new equilibrium condition. Except for adjustment processes that are detrimental to immediate management goals or to important installations, the land manager therefore should not interfere. If possible, he should work with the stream processes, not against them. Such an approach is less costly. For example, dredging the river bottom in aggrading reaches is not always unavoidable, but is nearly always of infinite duration and excessive cost (fig. 24).

[2]*Oral communication with Manti-LaSal National Forest personnel, and personal site observations.*

Figure 24.—Tractor excavation of sediment from this streambed was unavoidable because of the road location. Since sediment loads are very high during high flows, as indicated by high frequency of large bars in the river, this branch channel will refill. In the long run, relocation of the road may be less costly than repeated excavations.

Armoring

In many situations, the process of degradation is halted by the selective transport of the flow before the equilibrium slope is attained. This slope would have corresponded to the original bed material gradation. An example is Livesey's (1963) report on the Missouri River below Fort Randall, where 15 feet of degradation was expected. But after the bed had lowered 3.5 feet, degradation ceased because an armor was established on the bed. Within 10 years, the D_{65} (65% of the material on the cumulative curve is finer than the size D_{65}) increased from 0.20 mm to nearly 1 m, representing a coarsening of bed particles by 500%.

During the armoring processes, smaller particles are carried away by the flow, while the larger ones remain in place and create a stable bed. Two prerequisites must be fulfilled before an armor can be established: bed material must include a gradation from finer to larger grain sizes (which is true for most natural streams), and fluctuations in flow magnitude must be mild and flow velocities relatively low during time periods long enough for armor formation.

The armor coat is determined by the largest flows of the establishment period because particles light enough and available for transport are moved out by these flows, but by no means are all smaller grain sizes removed, although the large components are predomi-

nant in the armor. The individual larger grains exert a shingle effect by fully or partially covering smaller ones thus keeping them in place (Lane and Carlson 1953). There is no distinct boundary, therefore, between the armor and the sublayer. The armor becomes effective when it is one grain size thick (Lane and Carlson 1953). Future flows, larger than those experienced during the establishment of a given armor, may destroy the present coat and a new armor, consisting of a predominance of still larger particles, may be created. In contrast to the aggradation and degradation processes, armoring does not cause bed slope changes; instead, the bed is lowered parallel to its original slope (Gessler 1970, 1971).

Although precise quantitative projections on armor development are not possible (Little and Mayer 1976), the investigator should attempt to determine the availability of large sediment particles in sufficient quantities which can resist the largest flows in a given time period. Under conditions of degradation, this material must be exposed by a flow before it can act as armor. The size distribution of the sediment buried below the bed layer or in the banks is therefore important. If newly exposed banks are sufficiently soft for alignment changes to take place, degradation will not continue generally.

Where high values are at stake, Gessler's (1967) method of prediction should be used. This requires data on flow and sediment transport, which in many cases must be generated before analysis can proceed. Where the situation permits and data are not available, the expected depth of degradation and armor plating can be estimated by comparing present bed materials with those expected to be exposed by degradation. Drilling or other excavations would be required to determine the size of the lower bed materials. Because the judgment requires experience, an expert should be consulted.

THE NEED TO MONITOR STREAM BEHAVIOR

We should not underestimate the benefits that can be derived from predicting stream behavior. If bridge piers will be undermined by scour (degradation) or the bridge buried by sediments (aggradation), such knowledge is most valuable for management action even if it is not precise in time and volume. But data are required to make sound predictions. Many stream projects have been completed, but post-project behavior is seldom monitored. Monitoring is also needed because most theoretical relationships were developed under controlled laboratory conditions, and verification or modification of the relationships by case histories is required. Observations spanning long stream reaches and long time periods are expensive, but how else can we increase our knowledge about the real world?

Monitoring should be based on sampling at random or predetermined stations to reduce expenditures. Generally, the latter approach is preferable because fewer stations will be required for representation. An example would be the establishment of one sediment sampling station each in the head water, middle, and lower stream reach, since stream gradients and sediment particle sizes generally decrease downstream while flow and velocity increase. Often, average gradients of the reaches can be determined from maps. But sampling of total sediment load, one of the most influential hydraulic variables, is difficult. Bedload can be sampled only in catch basins or where turbulent flow places the total load in suspension. The latter condition may be found where channels are excessively constricted. Thus, usually only suspended load is monitored (by use of dip or pumping samples) to represent sediment load. Often, suspended load is 75% to 90% of the total.

Bed material particle sizes can be sampled at low flow. A grid pattern should be used comprising an area on the bed from bank to bank. Sampling total bed width will ensure the particle changes with changing flow lines across the channel will be representative. Wolman (1954) tested such a pattern and found significant representation of the particle size distribution. Changes in particle sizes are indicative of changes in bedload transport.

Monitoring bed material at a stream-gaging station will not show true sediment production in a watershed because of the lag time between production at a location and transport to the station. Especially in ephemeral streams, many years may pass before a substantial part of the sediment production reaches the station; and some amount never will (Heede 1976). Also, channel storage by bar and other depositional features (bed aggradation, riffles) generally is many times larger than the bedload caught at the gaging station.

If any sediment transport equations are to be used, they should be thoroughly tested for applicability. Because stream behavior involves intricate processes as demonstrated in the preceding sections, the processes have different modes at different flow conditions.

If stream-gaging stations are not available, a current meter or velocity headrod should be used for flow determinations. Heede (1974) showed velocity measurements by the rod require less time. In boulder-strewn streams, results did not differ significantly from the current meter readings.

Where channel cross sections must be sampled because of expected severe consequences from future channel shape changes, it is important to select representative sections of a reach. These can best be determined from aerial photographs, if low-flying images are available, or by ocular selection on the ground.

To facilitate ground surveys, bench marks should be established at some distance from the brink of the stream banks. Regular land survey tools such as a hand level or engineer's level will suffice.

The intensity of stream sampling depends on the objective and on available funds. But if the user focuses on the basic stream processes as outlined in this report, the complexity of stream dynamics can be

better understood and efforts limited to essential monitoring.

CONCLUSIONS

This report focuses on the major processes of stream dynamics and shows how the complexity of stream behavior forces the user to consider the individual components of each case. The report should be helpful in delineating the individual characteristics. Above all, stream restraining measures must be applied with great caution so that treatment of one critical location will not simply lead to the formation of another, or that future treatment "side effects" will not be more detrimental to the attainment of a new equilibrium condition than no treatment.

From the preceding sections, it follows that the science of fluvial hydraulics has not been developed to a level that permits accurate prediction of stream behavior. Judgment is still required in addition to mathematical-statistical analyses. Yet some qualitative predictions are possible since conceptual relationships have been developed for most hydraulic interactions. If streamflow records are available, the investigator can predict at least the trend of future stream behavior.

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NOTATION

A = cross-sectional area of flow—square feet
A' = difference in altitude between concave profile at mid-distance and straight line connecting the ends of profile—feet
D = sediment particle size—millimeters
d = depth of flow—feet
Fr = Froude number
g = acceleration due to gravity—feet per second per second
H = total fall of stream—feet
K_a = coefficient relating sediment load and water discharge
m = mass of water—pounds
p = wetted perimeter—feet
Q = stream discharge—cubic feet per second
Q_s = sediment discharge—pounds
Q_w = water discharge—cubic feet per second
Re = Reynolds number
R = hydraulic radius—feet
r = numerical constant
S = slope—feet rise or fall divided by feet horizontal distance
s = numerical constant
V = average velocity—feet per second
w = top width of channel—feet
γ = specific weight of water—pounds per cubic foot
μ = absolute (dynamic) viscosity—pound-seconds per square foot
ν = kinematic viscosity—square feet per second
ϱ = fluid density—pounds per cubic foot
τ = tractive force—pounds per square foot

Heede, Burchard H. 1980. Stream dynamics: An overview for land managers. USDA Forest Service General Technical Report RM-72, 26 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Concepts of stream dynamics are demonstrated through discussion of processes and process indicators. Theory is included only where helpful to explain concepts. Present knowledge allows only qualitative prediction of stream behavior. However, such predictions show how management actions will affect the stream and its environment.

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Rocky
Mountains

Southwest

Great
Plains

U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

The Rocky Mountain Station is one of eight regional experiment stations, plus the Forest Products Laboratory and the Washington Office Staff, that make up the Forest Service research organization.

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Research programs at the Rocky Mountain Station are coordinated with area universities and with other institutions. Many studies are conducted on a cooperative basis to accelerate solutions to problems involving range, water, wildlife and fish habitat, human and community development, timber, recreation, protection, and multiresource evaluation.

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Albuquerque, New Mexico
Bottineau, North Dakota
Flagstaff, Arizona
Fort Collins, Colorado*
Laramie, Wyoming
Lincoln, Nebraska
Lubbock, Texas
Rapid City, South Dakota
Tempe, Arizona

*Station Headquarters: 240 W. Prospect St., Fort Collins, CO 80526

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A Digitized Systematic Classification for Ecosystems with an Illustrated Summary of the Natural Vegetation of North America

David E. Brown
Charles H. Lowe
Charles P. Pase

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Foreword

The classification system illustrated here is the product of field research conducted throughout the North American Southwest, literature synthesis, and modification through discussion with users and academicians over the past decade. A multiple-level and open-ended arrangement of hierarchical components in the system provides for unlimited information content, thereby insuring sensitivity to scale. The fourth level of the classification is the basis for the recent vegetation map of the southwestern United States and adjacent northwestern Mexico at scale 1:1,000,000 (Brown et al. 1977).

In April 1979, the agency leaders of the Bureau of Land Management, Fish and Wildlife Service, Forest Service, Geological Survey, and Soil Conservation Service endorsed a four-component classification system to be used for renewable resource inventories and assessments (Driscoll et al. 1978). The hierarchical components are vegetation, soil, landform, and aquatic (water). The vegetation system with some modification is that prepared by the United Nations Educational, Scientific, and Cultural Organization (1973). This modified system and the system presented here are generally comparable at the Community (Series) and Association levels, but differences do occur. These differences will be resolved in the future as more information is obtained and understood about plant community systems.

Fort Collins, Colorado

Richard S. Driscoll

USDA Forest Service
General Technical Report RM-73

June 1980

A Digitized Systematic Classification for Ecosystems with an Illustrated Summary of the Natural Vegetation of North America

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Contents

A Digitized Systematic Classification for Ecosystems with an Illustrated Summary of the Natural Vegetation of North America

David E. Brown, Charles H. Lowe, and Charles P. Pase

INTRODUCTION

While the classification, analysis, and mapping of various biotic units has long been progressing in Europe, the Soviet Union, and the United States, recent efforts in the "developing" countries now indicate worldwide interest and activity in these fields (Aubreville 1958, Fittkau 1969, Flores et al. 1971, Whittaker 1973, Comision Tecnico Consultiva para la Determinacion Regional de los Coeficientes de Agostadero 1974). These endeavors have produced numerous resource classifications, particularly for vegetation. With some exceptions (Braun-Blanquet 1932, 1964; Daubenmire 1952, 1969; Gaussen 1953, 1955; Ellenberg and Mueller-Dombois 1967; Lactate 1969; Dasmann 1972; Pfister et al. 1977), classifications are based largely on limited criteria for potential vegetation (Kuchler 1964, 1967), or on partly artificial criteria such as land use per se (Anderson 1971, Anderson et al. 1972).

Again with some important exceptions (Dansereau 1957; Fosberg 1961; Krajina 1965; International Union for Conservation of Nature and Natural Resources 1973, 1974; United Nations Educational, Scientific, and Cultural Organization 1973; Ray 1975), resource classifications and classification schemes tend to be regional rather than continental and worldwide in their approach and applicability. Moreover, some recently developed wetland classification systems, while otherwise excellent, may be difficult to apply due to dependence on geologic and chemical criteria (Martin et al. 1953, Stewart and Kontrud 1971, Golet and Larson 1974, Cowardin et al. 1975, Zoltai et al. 1975).

Most classifications, moreover, are nonhierarchical or only partially hierarchical and, therefore, not readily subject to expansion and field modification (Wieslander 1935), Jensen 1947, Society of American Foresters 1954, Dansereau 1957, Garrison et al. 1974). This has resulted in resource management agencies combining and adapting various partial classification systems. The result is that no standardized system that is satisfactory is presently in effect within regions, much less throughout North America. In fact, there is as yet no agreement even on the basis for an evolutionarily derived system of classification. That the need exists is well known,[2] for example by the National Environmental Policy Act of 1969 and the National Resource Planning Act of 1974 (also see Layser 1974, Pfister 1975).

Although botanists and zoologists have long recognized and utilized the natural order of hierarchical systematics based on evolutionary criteria, resource managers have yet to agree on an analogous, taxonomic hierarchy for a natural universal classification system for the also evolutionarily derived ecosystems; their taxonomic division into plant association units comparable to species has been long recognized and discussed (Gleason 1939).

The ecological hierarchy herein ranks vegetative communities in systematized natural sets. This system is formulated on natural criteria and recognizes the limiting influences of moisture and temperature minima as well as the evolution of structure and composition of vegetation in general. The system was originally developed for southwestern North America where its adaptability has been well demonstrated (Lowe 1961; Brown and Lowe 1973, 1974a, 1974b). Incorporated are contributions of resource planners and users, plant geographers, zoogeographers, wildlife biologists and ecologists, all of which are in general usage today (Shelford and Shreve 1926; Halliday 1937; Gentry 1942; Shreve 1942; Dice 1943; Munz and Keck 1949, 1950; Oosting 1956; Curtis 1959; Shelford 1963; Lowe 1964; Braun 1967; Daubenmire and Daubenmire 1968; Franklin and Dyrness 1973; Mueller-Dombois and Ellenberg 1974). It is a natural world system.

A digitized system facilitates overall land use classification, resource planning, inventory and assessment, the interpretation of environmental uses and limitations, the delineation and stratification of habitats, and other activities of those concerned with natural resource inquiry. It has proven especially useful for environmental analysis where the inventory, assessment, and comparison of environmental systems is desired or required by governmental, educational, scientific, architectural, engineering, and other organizations. In short, the system is of particular use for those interested in and/or requiring classification of areas for resource management, study, acquisition, and/or preservation as "natural areas" throughout the world.

The digitization of hierarchy in the system makes it computer compatible, for example as a system or subsystem for storing and retrieving general information and data within or parallel to an overall management system. This system as applied to the North American Southwest is currently in use in the RUN WILD program

[2]*Driscoll, R. S., et al. 1976. MODIFIED ECOCLASS—A method for classifying ecosystems for the Rocky Mountain and Southwest Regions. U.S. Department of Agriculture, Forest Service, Rocky Mountain and Southwest Regions, and Rocky Mountain Forest and Range Experiment Station, ad hoc committee. mimeo. 117 p.*

being developed for field unit use on remote terminals by the Southwestern Region and the Rocky Mountain Forest and Range Experiment Station, USDA Forest Service (Patton 1978). This classification is similarly incorporated in the State of Arizona Resources Inventory System. It is also currently used by industry in environmental analysis procedures, for example as required by the National Environmental Policy Act.

Also, the use of a hierarchical sequence allows for flexibility in mapping of those complex communities where intensive levels of mapping would be impractical or needlessly time consuming. The hierarchical sequence allows for mapping at any scale.

An important advantage of a hierarchical system based on biotic criteria is the meaningful assignment of plant and animal habitats. This classification not only recognizes plant components within an assigned ecological distribution, it tells the reader which wildlife species could be expected to be present. As an example, the occurrence of nesting wood ducks (*Aix sponsa*) is expected in certain Temperate swampforests and riparian forests, as opposed to Tropical-Subtropical swampforests, expected in North America to be the nesting habitat of black-bellied whistling ducks (*Dendrocygna autumnalis*).

We present illustrated examples of the system at the second level (formation-type) to illustrate application on a world basis. Our fourth level (biome) illustrations and fifth level (series) examples for North America are representative and are presented to illustrate the reality, adaptability, and use of the classification system; they are not meant to be either a definitive or final classification. Examples of the use of the system to the sixth (association) level are given here for selected biomes within formation types (Rocky Mountain Montane Conifer Forest) and in previous publications relating to the North American Southwest (Lowe 1961; Brown and Lowe 1974a, 1974b) and North America (Brown et al. 1979).

A DIGITIZED HIERARCHY OF THE WORLD'S NATURAL ECOSYSTEMS

Where:

1,000 = Biogeographic (Continental) Realm
- 1,100 = Vegetation
  - 1,110 = Formation-type
    - 1,111 = Climatic (Thermal) Zone
      - 1,111.1 = Regional Formation (Biome)
        - 1,111.11 = Series (Community of generic dominants)
          - 1,111.111 = Association (of specific dominants)
            - 1,111.1111 = Composition-structure-phase

The number preceding the comma (e.g., 1,000) refers to the world's biogeographic realms (table 1). Origin and evolutionary history are recognized here as being of primary importance in the determination and classification of natural ecosystems. The mappable reality of the world's biogeographic realms is, of course, interpretive in part, for it is dependent on the criteria used. In those regions where the components of one realm merge gradually with those of another and the assignment of biogeographic origin is difficult, we include such transitional areas (wide ecotones) in both realms. The following seven realms are adapted from Wallace (1876), (see also Hesse et al. 1937, Darlington 1957, Dansereau 1957, Walter 1973, International Union for Conservation of Nature and Natural Resources 1974, DeLaubenfels 1975, Cox et al. 1976):

1000 Nearctic	Continental North America exclusive of the tropics and most highland areas south of the Tropic of Cancer. We include those tropic-subtropic regions in and adjacent to the North American Southwest and the Caribbean.
2000 Palaearctic	Eurasia exclusive of the tropics; Africa north of the Sahel.
3000 Neotropical and Antarctican	Continental South America, Central America, and most of Mexico south of the Tropic of Cancer. Antarctica.
4000 Oriental	Southeast Asia, the Indian subcontinent; the Phillipines, Indonesia, etc.
5000 Ethiopian	Africa south of the Sahara, Malagasy, and parts of the Arabian peninsula.
6000 Australian	Australia and Tasmania.
7000 Oceanic	Oceanic islands possessing a high degree of endemism.

FIRST LEVEL

The first digit after the comma (e.g., 1,100) refers to vegetation in one of four generalized types. Included are all plant communities that are presumed to be established naturally under existing climate and the cessation of artificially disruptive (human-caused) influences (table 1).

All existing and potential natural vegetation (PNV) is classified as belonging to uplands (1,100) or wetlands (1,200) as in table 1; or cultivated lands (1,300, 1,400). Only the first two are considered here. The important adaptation inherent in plants and animals of terrestrial (upland) as opposed to hydric (wetland) biotic communities is recognized by this dichotomy (Martin et al. 1953, Ray 1975). As discussed here, wetlands include those periodically, seasonally, or continually submerged biotic communities populated by species and/or life forms different from the immediately adjacent (upland) vegetation. Certain systems having both upland and wetland characteristics and components (e.g., riparian forests) could be properly considered as belonging to both divisions. They are included here in the wetlands division (1,200).

SECOND LEVEL

Second digit after the comma (1,110) refers to one of the following recognized ecological formations, which on a worldwide basis are the formation-types ("biome-types") (table 2). On continents, these are referred to as formations which are vegetative responses (functions) to integrated environmental factors, most importantly, available soil moisture.

Upland Formations

Tundra[3]	Communities existing in an environment so cold that moisture is unavailable during most of the year, precluding the establishment of trees, and in which the maximum development is that of perennial herbaceous plants, shrubs, lichens, and mosses, with grasses poorly represented or at least not dominant (fig. 1).
Forest and Woodland Communities	
Forest	Communities comprised principally of trees potentially over 15 m in height, and frequently characterized by closed and/or multilayered canopies (fig. 2).
Woodland	Communities dominated by trees with a mean potential height usually under 15 m, the canopy of which is usually open (sometimes very open)[4] or interrupted and singularly layered (fig. 3).
Scrubland	Communities dominated by sclerophyll or microphyll shrubs and/or multistemmed trees, generally not exceeding 10 m in height, usually presenting a closed physiognomy, or if open, interspaced with other perennial vegetation (fig. 4).
Grassland	Communities dominated actually or potentially by grasses and/or other herbaceous plants (fig. 5).
Desertland	Communities in an arid environment (usually less than 300 mm precipitation per annum) in which plants are separated by significant areas devoid of perennial vegetation (fig. 6).

[3]The holistic integrity of a "tundra" formation is not without serious question. Treated here, tundra may also be composed of grasslands, scrublands, marshlands (wet tundra), and desertlands in an Arctic—Boreal Climatic Zone (table 4) (Billings and Mooney 1968, Billings 1973).

[4]The "savanna" formation (Dyksterhuis 1957) is here recognized as an ecotone between woodland and grassland. Those homogeneous areas in which the crowns of trees normally cover less than approximately 15% of the ground space are classified as grasslands where grasses are actually or potentially dominant (=savanna-grassland). Mosaics of grasslands and smaller or larger stands of trees and shrubs are "parklands" and are composed of two or more ecologically distinct plant formations (Walter 1973).

Wetland Formations

Wet Tundra[5]	Aquatic communities existing in an environment so cold that available plant moisture is unavailable during most of the year, precluding the establishment of trees and all but a low herbaceous plant structure in a hydric matrix.
Swamp-Forest; Riparian Forest	Aquatic communities possessing an overstory of trees potentially over 10 m in height, and frequently characterized by closed and/or multilayered canopies (fig. 7).
Swamp-Scrub; Riparian Scrub	Aquatic communities dominated by short trees and/or woody shrubs, generally under 10 m in height and often presenting a closed physiognomy (fig. 8).
Marshland	Aquatic communities, in which the principal plant components are herbaceous emergents which normally have their basal portions annually, periodically, or continually submerged (fig. 9).
Strand	Beach and river channel communities subject to infrequent but periodic submersion, wind-driven waves or spray. Plants are separated by significant areas devoid of perennial vegetation (fig. 10).
Submergents	Aquatic communities comprised entirely or almost entirely of plants mostly submerged or lacking emergent structures (fig. 11).

Some upland and wetland areas (e.g., dunes, lava flows, playas, sinks, etc.) are essentially without vegetation or are sparingly populated by simple organisms. For purposes of classification, these areas could be considered as belonging to a nonvascular formation-type (table 2).

[5]The holistic integrity of a "tundra" formation is not without serious question. Treated here, tundra may also be composed of grasslands, scrublands, marshlands (wet tundra), and desertlands in an Arctic—Boreal Climatic Zone (table 5) (Billings and Mooney 1968, Billings 1973).

THIRD LEVEL

Third digit beyond the comma (e.g., 1,111) refers to one of the four world climatic zones (Walter 1973, Ray 1975, Cox et al. 1976) in which minimum temperature remains a major evolutionary control of and within the zonation and formation-types (table 3).

Arctic—Boreal (Antarctic—Austrial)	Characterized by lengthy periods of freezing temperatures, with the coldest month isotherm -3° C (Koppen 1931), growing season of short duration (generally less than 100 days), occasionally interrupted by nights of below-freezing temperatures.
Cold Temperate	Freezing temperatures of short duration, although of frequent occurrence, during winter months. Potential growing season generally of from 100 to 200 days and confined to spring and summer when freezing temperatures are infrequent or absent.
Warm Temperate	Freezing temperatures of short duration but generally occurring every year during winter months. Potential growing season over 200 days with an average of less than 125-150 days being subject to temperatures lower than 0° C or chilling fogs.
Tropical-Subtropical	Infrequent or no 24-hour periods of freezing temperatures, chilling fogs, or wind.

FOURTH LEVEL

Fourth level (e.g., 1,111.1) refers to a subcontinental unit that is a major biotic community (= biome). These biomes are characterized by a distinctive evolutionary history—within a formation—and are centered in, but not necessarily restricted to, a biogeographic region or province possessing a particular precipitation pattern or other climatic regime (Pitelka 1941, Dice 1943, Odum 1945, Franklin 1977) (fig. 12). It is this and the fifth levels that have provided the most successful and useful mapping of states, provinces, and continents (Shantz and Zon 1924, Bruner 1931, Shreve 1951, Kuchler 1964, Franklin and Dyrness 1973, Brown 1973, Brown et al. 1977).

Biogeographic provinces and biomes are also the bases for the biosphere reserve program in the United States and elsewhere (International Union for Conservation of Nature and Natural Resources 1974, Franklin 1977). A partial summary of the biotic communities for Nearctic and adjacent Neotropical America is given in tables 4 and 5.

FIFTH LEVEL

Fifth level (e.g., 1,111.11) provides the principal plant-animal communities within the biomes, recognized and distinguished primarily on distinctive climax plant dominants (= series). These series, sometimes referred to as cover-types (Society of American Foresters 1954), are each composed of one or more biotic associations characterized by shared climax dominants within the same formation, zone, and biome (Oosting 1956, Lowe 1964, Franklin and Dyrness 1973, Pfister et al. 1977). For example, a ponderosa pine series would include those Rocky Mountain forest associations in which *Pinus ponderosa* was a dominant component (table 4). The diversity of tropical and subtropical climax dominants is often inherently more complex than in boreal and temperate communities.

It should be pointed out that some plants are highly faculative and the same species may be a dominant in more than one formation-type. As an extreme example, mesquite (*Prosopis juliflora*) may be the dominant life-form in certain woodland, scrubland, desertland, and even forest and disclimax grassland formations. The distribution of some plant dominants also span more than one climatic zone (e.g., mesquite, creosote (*Larrea tridentata*), and the introduced *Tamarix*). The plant and animal associates of these dominants usually differ when passing from one formation-type or climatic zone to another, however. Numerous generic dominants and some species are shared also by more than one biome (e.g., *Populus*, *Salix*, *Pinus*, *Quercus*, and *Larrea*). Closer investigation usually reveals that biomes do not normally share the same speciation within genera, and those that do may exhibit major genetic differences between biomes (Yang and Lowe 1970). For these reasons, the determination of fifth and sixth level communities will require interpretive revision and modification of the classification as field investigations accumulate.

SIXTH LEVEL

Sixth level (e.g., 1,111.111) refers to distinctive plant associations (and associes)[6] based on the occurrence of particular dominant species more or less local (or regional) in distribution and generally equivalent to habit-types as outlined by Daubenmire and Daubenmire (1968), Layser (1974), and Pfister et al. (1977). While we demonstrate examples for certain communities within selected biomes (e.g., the Douglas-fir and Pine Series within the Rocky Mountain Montane Conifer Forest), the enormous numbers of sets preclude presentation here for the continental treatments in tables 4 and 5. These may be added at length for regional studies. Those communities judged to be seral or successional in nature may be preceded by an "s" at the seventh level.

[6]*Includes associations (and successional associes) constituted by single species that are more precisely termed consociations (and successional consocies) (Weaver and Clements 1938).*

SEVENTH LEVEL

Seventh level (e.g., 1,111.1111) accommodates detailed measurement and assessment of quantitative structure, composition, density and other numerical determinations for dominants, understories, and other species. Implementation of this level in the system is designed for particular intensive studies for limited areas (Dick-Peddie and Moir 1979).

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TABLES

Table 1.—Summary for the natural vegetation of the world to the first level

Biogeographic realm	1. Upland vegetation	2. Wetland vegetation
1,000 Nearctic	1,100	1,200
2,000 Palaearctic	2,100	2,200
3,000 Neotropical—Antarctican	3,100	3,200
4,000 Oriental	4,100	4,200
5,000 Ethiopian	5,100	5,200
6,000 Australian	6,100	6,200
7,000 Oceanic	7,100	7,200

Table 2.—Summary for the natural upland and wetland vegetation of the world to the second level (formation-type)

Biogeographic realm	Formation-type					
	1. Tundra	2. Forest and Woodland	3. Scrub-land	4. Grassland	5. Desertland	6. Non-vascular
UPLAND						
1,000 Nearctic	1,110	1,120	1,130	1,140	1,150	1,160
2,000 Palaearctic	2,110	2,120	2,130	2,140	2,150	2,160
3,000 Neotropical—Antarctican	3,110	3,120	3,130	3,140	3,150	3,160
4,000 Oriental	4,110	4,120	4,130	4,140	4,150	4,160
5,000 Ethiopian	5,110	5,120	5,130	5,140	5,150	5,160
6,000 Australian	6,110	6,120	6,130	6,140	6,150	6,160
7,000 Oceanic	7,110	7,120	7,130	7,140	7,150	7,160
	1. Wet tundra	2. Forest*	3. Swamp-Scrub	4. Marshland	5. Strand	6. Submergent
WETLAND						
1,000 Nearctic	1,210	1,220	1,230	1,240	1,250	1,260
2,000 Palaearctic	2,210	2,220	2,230	2,240	2,250	2,260
3,000 Neotropical—Antarctican	3,210	3,220	3,230	3,240	3,250	3,260
4,000 Oriental	4,210	4,220	4,230	4,240	4,250	4,260
5,000 Ethiopian	5,210	5,220	5,230	5,240	5,250	5,260
6,000 Australian	6,210	6,220	6,230	6,240	6,250	6,260
7,000 Oceanic	7,210	7,220	7,230	7,240	7,250	7,260

**Swamp-forests, bog forests, and riparian forests.*

Table 3.—Summary for the natural upland and wetland vegetation of Nearctic and adjacent Neotropical North America to the third level

Formation	Climatic (thermal) zone			
	1. Arctic—Boreal	2. Cold Temperate	3. Warm Temperate	4. Tropical—Subtropical
UPLAND				
1,110 Tundra	1,111			
1,120 Forests and Woodland	1,121	1,122	1,123	1,124
1,130 Scrubland	1,131	1,132	1,133	1,134
1,140 Grassland	1,141	1,142	1,143	1,144
1,150 Desertland	1,151	1,152	1,153	1,154
1,160 Nonvegetated	1,161	1,162	1,163	1,164
WETLAND				
1,210 Wet Tundra	1,211			
1,220 Forest*	1,221	1,222	1,223	1,224
1,230 Swamp-Scrub	1,231	1,232	1,233	1,234
1,240 Marshland	1,241	1,242	1,243	1,244
1,250 Strand	1,251	1,252	1,253	1,254
1,260 Submergent	1,261	1,262	1,263	1,264

**Swamp-forests, bog forests, and riparian forests.*

Table 4.—Nomenclature of upland biotic communities (fourth level) of Nearctic and adjacent Neotropical North America with some community (series) and association level examples

1,100 Nearctic Upland Vegetation
 1,110 Tundra Formation
  1,111 Arctic Tundras
   1,111.1 Polar (High Arctic) Tundra
    1,111.11 Sedge—Moss (Meadow) Series*
    1,111.12 Cushion Plant—Lichen Series*
   1,111.2 Alaskan (Low Arctic) Coastal Tundra (fig. 13)
    1,111.21 Sedge—Grass—Moss Series*
    1,111.22 Heath—Avens Series*
   1,111.3 Canadian (Barren Ground = Low Arctic) Tundra
    1,111.31 Heath—Lichen Series*
   1,111.4 Arctic Alpine Tundra
    1,111.41 Heath—Lichen Series*
   1,111.5 Rocky Mountain Alpine Tundra*** (fig. 14)
    1,111.51 Lichen—Moss Series*
    1,111.52 Mixed Herb Series*
    1,111.53 Avens—Sedge Series*
    1,111.54 Woodrush Series*
   1,111.6 Sierran—Cascade Alpine Tundra
    1,111.61 Lichen—Moss Series*
    1,111.62 Mixed Herb Series*
   1,111.7 Adirondack—Appalachian Alpine Tundra
    1,111.71** Lichen—Moss Series*
120 Forest and Woodland Formation
 121 Boreal Forests and Woodlands
  121.1 Canadian Subarctic Conifer Forest and Woodland (North American Taiga) (figs. 15 and 16)
   121.11 White Spruce—Balsam Fir Series*
   121.12 Black Spruce Series*
  121.2 Appalachian Subalpine Conifer Forest (fig. 17)
   121.21 Red Spruce—Balsam Fir Series*
  121.3 Rocky Mountain Subalpine Conifer Forest and Woodland***
   121.31 Engelmann Spruce—Alpine Fir Series* (fig. 18)
   121.32 Bristlecone Pine—Limber Pine Series* (fig. 19)
  121.4 Sierran—Cascade Subalpine Conifer Forest (fig. 20)
   121.41 Limber Pine—Lodgepole Pine Series*
   121.42 Whitebark Pine Series*
   121.43 Mountain Hemlock Series*
  121.5 Madrean Subalpine Conifer Forest
   121.51 Pine—Religious Fir Series*

 122 Cold Temperate Forests and Woodlands
  122.1 Northeastern Deciduous Forest (fig. 21)
   122.11 Oak—Hickory Series*
   122.12 Oak—Chestnut Series*
   122.13 Beech—Maple Series*
   122.14 Oak—Pine Series*
   122.15 Maple—Basswood Series*
   122.16 Hemlock—White Pine—Hardwood Series*
  122.2 Pacific Coastal (Oregonian) Conifer Forest (figs. 22 and 23)
   122.21 Coast Redwood Series*
   122.22 Douglas-fir Series*
   122.23 Western Hemlock Series*
   122.24 Sitka Spruce Series*
   122.25 Grand Fir Series*
  122.3 Rocky Mountain (= Petran) Montane Conifer Forest (fig. 24)
   122.31 Douglas-fir—White fir (= Mixed Conifer) Series*
    122.311 *Pseudotsuga menziesii* Association*
    122.312 *Pseudotsuga menziesii—Abies concolor* Association*
    122.313 *Pseudotsuga menziesii*—Mixed Conifer (*Abies concolor, Pinus flexilis, Acer glabrum, Populus tremuloides, Pinus ponderosa*) Association*
    122.314 *Populus tremuloides* subclimax Association*
   122.32 Pine Series*
    122.321 *Pinus ponderosa* Association*
    122.322 *Pinus ponderosa*—Mixed Conifer Association*
    122.323 *Pinus ponderosa—Quercus gambelii* Association*
    122.324 *Pinus ponderosa—Quercus arizonica* Association*
    122.325 *Pinus ponderosa—Juniperus deppeana* Association*
    122.326 *Populus tremuloides* subclimax Association*
    122.327 *Pinus flexilis* Association*
    122.328 *Pinus ponderosa—Abies concolor* Association*
   122.33 Gambel Oak Series*
    122.331 *Quercus gambelii* Association*
  122.4 Great Basin Conifer Woodland (fig. 25)
   122.41 Pinyon—Juniper Series*
  122.5 Sierran—Cascade Montane Conifer Forest (fig. 26)
   122.51 Mixed Conifer Series*
   122.52 Red Fir Series*
   122.53 Pacific Silver Fir Series*
   122.54 White Fir Series*
   122.55 Pine Series*
   122.56 Black Oak Series*
  122.6 Madrean Montane Conifer Forest
   122.61 Douglas-fir—Mixed Conifer Series*
   122.62 Pine Series*

 123 Warm Temperate Forests and Woodlands
  123.1 Southeastern Mixed Deciduous and Evergreen Forest (figs. 27 and 28)
   123.11 Pine Series*
   123.12 Mixed Mesophytic Series*
   123.13 Mixed Hardwood Hammock Series*
  123.2 Californian Mixed Evergreen Forest (fig. 29)
   123.21 Mixed Mesophytic Series*
   123.22 Big-cone Spruce Series*
  123.3 Californian Evergreen Woodland (fig. 30)
   123.31 Encinal (Oak) Series*
   123.32 Walnut Series*
   123.33 Oak—Pine Series*
  123.4 Madrean Evergreen Forest and Woodland (fig. 31)
   123.41 Encinal (Oak) Series*
   123.42 Oak—Pine Series*
  123.5 Relict Conifer Forest and Woodland (figs. 32 and 33)
   123.51 Closed-cone Pine Series*
   123.52 Cypress Series*

 124 Tropical—Subtropical Forests and Woodlands
  124.1 Caribbean Montane Rain Forest (fig. 34)
   124.11 Palm Series*
   124.12 Tabenuco—Palocolorado Series*
  124.2 Caribbean Cloud Forest
   124.21 Ocotea—Roble de Sierra Series*
  124.3 Caribbean Evergreen Forest (figs. 35 and 36)
   124.31 Pine Series*
   124.32 Tabebuia—Gallo Series*
  124.4 Caribbean Deciduous Forest
   124.41 Mixed Short Tree Series*
  124.5 Tamaulipan Semideciduous Forest (fig. 37)
   124.51 Mixed Short Tree Series*
  124.6 Sinaloan Deciduous Forest (fig. 38)
   124.61 Mixed Short Tree Series*

130 Scrubland Formation
 131 Arctic—Boreal Scrublands
  131.1 Alaskan (Low Arctic) Coastal Scrub (fig. 39)
   131.11 Crowberry Series*
   131.12 Birch—Willow Series*

*Examples only.

**The first "1" (in front of comma and representing the Nearctic realm) is understood and dropped for tabular convenience only from this point onward.

***Further consideration may warrant separation of this biotic community into Rocky Mountain and Great Basin units.

131.2 Canadian (Low Arctic, Barren Ground) Subpolar Scrub
131.21 Birch—Willow Series*
131.22 Alder Series*
131.3 Alaskan Alpine and Subalpine Scrub (fig. 40)
131.31 Willow—Birch Series*
131.4 Adirondack—Appalachian Alpine and Subalpine Scrub
131.41 Hobblebush Series*
131.5 Rocky Mountain Alpine and Subalpine Scrub (fig. 41)
131.51 Willow Series*
131.52 Spruce Elfinwood Series*
131.53 Bristlecone Pine Elfinwood Series*
131.6 Sierran—Cascade Alpine and Subalpine Scrub
131.61 Limber Pine—Lodgepole Pine Elfinwood Series*
131.62 Whitebark Pine Elfinwood Series*

132 Cold Temperate Scrublands
132.1 Great Basin Montane Scrub (fig. 42)
132.11 Oak—Scrub Series*
132.12 Mountainmahogany Series*
132.13 Maple—Scrub Series*
132.14 Serviceberry Series*
132.15 Bitterbush Series*
132.16 Mixed Deciduous Series*
132.2 Sierran—Cascade Montane Scrub
132.21 Manzanita Series*
132.22 Mixed Scrub Series*
132.3 Plains Deciduous Scrub (fig. 43)
132.31 Oak—Scrub Series*
132.32 Sumac Series*
132.33 Mixed Deciduous Series*

133 Warm Temperate Scrublands
133.1 Californian Chaparral (fig. 44)
133.11 Chamise Series*
133.12 Scrub Oak Series*
133.13 Manzanita Series*
133.14 Ceanothus Series*
133.15 Mixed Evergreen Sclerophyll Series*
133.2 Californian Coastal Scrub (fig. 45)
133.21 Sage Series*
133.22 Mixed Shrub Series*
133.3 Interior Chaparral (fig. 46)
133.31 Scrub Oak Series*
133.32 Manzanita Series*
133.33 Ceanothus Series*
133.34 Mountainmahogany Series*
133.35 Silktassel Series*
133.36 Mixed Evergreen Sclerophyll Series*
133.4 Southeastern Maritime Scrub
133.41 Scrub Oak Series*

134 Tropical—Subtropical Scrublands
134.1 Caribbean Thorn Scrub
134.11 Mixed Deciduous Series*
134.2 Tamaulipan Thorn Scrub (fig. 47)
134.21 Mixed Deciduous Series*
134.3 Sinaloan Thorn Scrub (fig. 48)
134.31 Mixed Deciduous Series*
134.32 Mesquite Disclimax Series*

140 Grassland Formation
141 Arctic—Boreal Grasslands
141.1 Alaskan (Low Arctic) Coastal Grassland (fig. 49)
141.11 Cottongrass Series*
141.2 Canadian (Low Arctic) Grassland
141.21 Bunchgrass Series*
141.3 Appalachian Subalpine (Balds) Grassland (fig. 50)
141.31 Oatgrass—Herb Series*
141.4 Rocky Mountain Alpine and Subalpine Grassland (fig. 51)
141.41 Bunchgrass Series*
141.42 Sedge—Forb—Grass Series*
141.5 Sierran—Cascade Alpine and Subalpine Grassland
141.51 Bunchgrass Series*
141.52 Sedge—Forb—Grass Series*
141.6 Madrean Alpine and Subalpine Grassland
141.61 Bunchgrass Series*

142 Cold Temperate Grasslands
142.1 Plains Grassland
142.11 Bluestem "tall-grass" Series* (fig. 52)
142.12 Grama Series* (fig. 53)
142.13 Buffalo-grass Series*
142.14 Mixed "short-grass" Series*
142.15 Shrub—Grass Disclimax Series*
142.2 Great Basin Shrub—Grassland
142.21 Wheatgrass Series*
142.22 Mixed Bunchgrass Series* (fig. 54)
142.23 Ricegrass Series*
142.24 Sacaton Series*
142.25 Cheatgrass Disclimax Series*
142.3 Pacific Coastal (Oregonian) Grassland
142.31 Mixed Bunchgrass Series*
142.4 Rocky Mountain Montane Grassland (fig. 55)
142.41 Mixed Meadow Series*
142.42 Rush Series*
142.43 Fern Series*
142.44 Iris Disclimax Series*
142.5 Sierran—Cascade Montane Grassland
142.51 Mixed Meadow Series*
142.52 Rush Series*

143 Warm Temperate Grasslands
143.1 Scrub—Grassland (Semidesert Grassland) (fig. 56)
143.11 Grama Grass—Scrub Series*
143.12 Tobosa Grass—Scrub Series*
143.13 Curley-mesquite Scrub Series*
143.14 Sacaton—Scrub Series*
143.15 Mixed Grass—Scrub Series*
143.16 Shrub—Scrub Disclimax Series*
143.2 Californian Valley Grassland (fig. 57)
143.21 Annual Disclimax Series*

144 Tropical—Subtropical Grasslands
144.1 Caribbean Savanna Grassland (fig. 58)
144.2 Gulf Coastal (Tamaulipan) Grassland (fig. 59)
144.21 Beardgrass Series*
144.3 Sonoran Savanna Grassland (fig. 60)
144.31 Mixed Perennial Grass Series*
144.32 Grama Series*
144.33 Three-awn Series*

150 Desertland Formation
151 Arctic—Boreal Desertlands
151.1 Polar Desert-Scrub (fig. 61)
151.11 Moss—Lichen Series*

152 Cold Temperate Desertlands
152.1 Great Basin Desertscrub (fig. 62)
152.11 Sagebrush Series*
152.12 Shadscale Series*
152.13 Blackbrush Series*
152.14 Rabbitbrush Series*
152.15 Winterfat Series*
152.16 Mixed Scrub Series*
152.17 Saltbush Series*
153 Warm Temperate Desertlands
153.1 Mohave Desert-Scrub (fig. 63)
153.11 Creosotebush Series*
153.12 Blackbrush Series*
153.13 Mesquite Series*
153.14 Bladdersage Series*
153.15 Joshuatree Series*
153.16 Catclaw Series*
153.17 Saltbush Series*

153.2 Chihuahuan Desert-Scrub (fig. 64)
- 153.21 Creosotebush—Tarbush Series*
- 153.22 Whitethorn Series*
- 153.23 Sandpaperbush Series*
- 153.24 Mesquite Series*
- 153.25 Succulent Series*
- 153.26 Mixed Scrub Series*
- 153.27 Saltbush Series*

154 Tropical—Subtropical Desertlands

154.1 Sonoran Desert-Scrub (fig. 65)
- 154.11 Creosotebush—Bursage ("Lower Colorado Valley" et al.) Series*
- 154.12 Paloverde—Mixed Cacti ("Arizona Upland") Series*
- 154.13 Brittlebush—Ironwood ("Plains of Sonora") Series*
- 154.14 Copal—Torote ("Central Gulf Coast") Series*
- 154.15 Agave—Bursage ("Vizcaino") Series*
- 154.16 Paloblanco—Agria ("Magdalena") Series*
- 154.17 Saltbush Series*

Table 5.—Nomenclature of wetland biotic communities (fourth level) of Nearctic and adjacent Neotropical North America with some community (series) and association level examples for the North American Southwest

1,200 Nearctic Wetland Vegetation
- 1,210 Wet Tundra Formation
  - 1,211 Arctic Wet Tundras
    - 1,211.1 Polar (High Arctic) Wet Tundra
      - 1,211.11 Sedge—Moss Series*
      - 1,211.12 Rush Series*
    - 1,211.2 Greenlandian Wet Tundra
      - 1,211.21 Sedge—Moss Series*
    - 1,211.3 Alaskan (Coastal) Wet Tundra (fig. 66)
      - 1,211.31 Sedge—Moss Series*
    - 1,211.4 Canadian (Low Arctic) Wet Tundra
      - 1,211.41 Sedge—Grass—Moss Series*
      - 1,211.42** Rush Series*

220 Forest Formation
- 221 Boreal Swamp and Riparian Forests
  - 221.1 Canadian Swamp Forest (fig. 67)
    - 221.11 Black Spruce—Tamarack Series*
    - 221.12 Willow—Alder Series*
- 222 Cold Temperate Swamp and Riparian Forests
  - 222.1 Northeastern Bog, Swamp, and Riparian Forests (fig. 68)
    - 222.11 White Cedar Series*
    - 222.12 Cottonwood—Willow Series*
    - 222.13 Ash—Maple Series*
  - 222.2 Plains and Great Basin Riparian Deciduous Forest
    - 222.21 Cottonwood—Willow Series*
  - 222.3 Rocky Mountain Riparian Deciduous Forest
    - 222.31 Cottonwood—Willow Series*
    - 222.32 Mixed Broadleaf Series*
  - 222.4 Sierran—Cascade Riparian Deciduous Forest
    - 222.41 Cottonwood—Willow Series*
    - 222.42 Mixed Broadleaf Series*
  - 222.5 Pacific Coastal (Oregonian) Riparian Deciduous Forest
    - 222.51 Cottonwood—Willow Series*
- 223 Warm Temperate Swamp and Riparian Forests
  - 223.1 Southeastern Swamp and Riparian Forest (fig. 69)
    - 223.11 Tupelo—Cypress Series*
    - 223.12 Southern White Cedar Series*
    - 223.13 Mixed Hardwood (Bottomland) Series*
    - 223.14 Cottonwood—Willow Series*
  - 223.2 Southwestern Riparian Deciduous Forest and Woodland (fig. 70)
    - 223.21 Cottonwood—Willow Series*
    - 223.22 Mixed Broadleaf Series*
  - 223.3 Californian Riparian Deciduous Forest and Woodland
    - 223.31 Cottonwood—Willow Series*
    - 223.32 Mixed Broadleaf Series*
- 224 Tropical—Subtropical Swamp, Riparian, and Oasis Forests
  - 224.1 Caribbean Interior Swamp and Riparian Forests
    - 224.11 Mixed Evergreen Series*
    - 224.12 Palm Series*
  - 224.2 Caribbean Maritime Swamp-Forest (fig. 71)
    - 224.21 Mangrove Series*
  - 224.3 Tamaulipan Interior Swamp and Riparian Forests
    - 224.31 Mixed Evergreen Series*
    - 224.32 Palm Series*
  - 224.4 Sinaloan Interior Swamp and Riparian Forests (fig. 72)
    - 224.41 Mixed Evergreen Series*
    - 224.42 Palm Series*
  - 224.5 Sonoran Riparian and Oasis Forests
    - 224.51 Palm Series* (fig. 73)
    - 224.52 Mesquite Series* (fig. 74)
    - 224.53 Cottonwood—Willow Series*

230 Swamp-Scrub Formation
- 231 Arctic—Boreal Swamp-Scrubs
  - 231.1 Polar (High Arctic) Swamp-Scrub
    - 231.11 Willow Series*
  - 231.2 Greenlandian Swamp-Scrub
    - 231.21 Willow Series*
  - 231.3 Alaskan Swamp-Scrub
    - 231.31 Willow Series*
  - 231.4 Canadian Swamp-Scrub (fig. 75)
    - 231.41 Willow Series*
    - 231.42 Leatherleaf Series*
  - 231.5 Adirondack—Appalachian Alpine and Subalpine Swamp and Riparian Scrub
    - 231.51 Willow Series*
  - 231.6 Rocky Mountain Alpine and Subalpine Swamp and Riparian Scrub (fig. 76)
    - 231.61 Willow Series*
  - 231.7 Sierran—Cascade Alpine and Subalpine Swamp and Riparian Scrub
    - 231.71 Willow Series*
- 232 Cold Temperate Swamp and Riparian Scrubs
  - 232.1 Northeastern Deciduous Swamp-Scrub
    - 232.11 Willow Series*
    - 232.12 Sweet Gale Series*
    - 232.13 Buttonbush Series*
    - 232.14 Cranberry Series*
    - 232.15 Mixed Narrowleaf Series*
  - 232.2 Plains and Great Basin Riparian Scrub (fig. 77)
    - 232.21 Willow Series*
    - 232.22 Saltcedar Disclimax Series*
  - 232.3 Rocky Mountain Riparian Scrub (fig. 78)
    - 232.31 Willow—Dogwood Series*
  - 232.4 Sierran—Cascade Riparian Scrub
    - 232.41 Willow Series*
  - 232.5 Pacific Coastal (Oregonian) Swamp and Riparian Scrub
    - 232.51 Willow Series*
    - 232.52 Mixed Narrowleaf Series*

*One or more examples only are given for the fifth level.

**The first "1" (in front of comma and representing the Nearctic realm) is understood and dropped for tabular convenience only from this point onward.

Table 5.—Continued

233 Warm Temperate Riparian and Swamp Scrubs
233.1 Southeastern Mixed Deciduous and Evergreen Swamp Scrub
233.11 Mixed Broadleaf Series*
233.2 Interior Southwestern Swamp and Riparian Scrub (fig 79)
233 21 Seepwillow Series*
233.22 Saltcedar Disclimax Series*
233.3 Californian Deciduous Swamp and Riparian Scrub
233.31 Mixed Narrowleaf Series*

234 Tropical—Subtropical Swamp and Riparian Scrub
234.1 Cribbean Interior Swamp Scrub
234.11 Mixed Evergreen Series*
234.2 Caribbean Maritime Swamp-Scrub
234.21 Mangrove Series*
234.3 Tamaulipan Interior Swamp and Riparian Scrub
234.31 Mixed Evergreen Series*
234.4 Tamaulipan Maritime Swamp-Scrub
234.41 Mangrove Series*
234.5 Sinaloan Interior Swamp and Riparian Scrub
234.51 Mixed Evergreen Series*
234.6 Sinaloan Maritime Swamp-Scrub (fig. 80)
234.61 Mangrove Series*
234.7 Sonoran Deciduous Swamp and Riparian Scrub (fig. 81)
234.71 Mixed Scrub Series*
234.72 Saltcedar Disclimax Series*

240 Marshland Formation
241 Arctic—Boreal Marshlands
241.1 Polar (High Arctic) Marshland
241.11 Sedge Series*
241.12 Rush Series*
241.2 Greenlandian Marshland
241.21 Sedge Series*
241.22 Rush Series*
241.3 Alaskan Maritime (Coastal) Marshland
241.31 Sedge Series*
241.32 Rush Series*
241.4 Canadian Interior Marshland (fig. 82)
241.41 Sedge Series*
241.42 Rush Series*
241.5 Canadian Maritime (Coastal) Marshland
241.51 Sedge Series*
241.6 Adirondack—Appalachian Alpine and Subalpine Marshland
241.61 Sedge Series*
241.62 Rush Series*
241.7 Rocky Mountain Alpine and Subalpine Marshland
241.71 Rush Series*
241.72 Manna Grass Series*
241.8 Sierran—Cascade Alpine and Subalpine Marshland
241.81 Rush Series*

242 Cold Temperate Marshlands
242.1 Northeastern Interior Marshland
242.11 Sedge Series*
242.12 Rush Series*
242.13 Bur-reed Series*
242.14 Cattail Series*
242.15 Bulrush Series*
242.16 Arrow-arum Series*
242.17 Water Lily Series*
242.18 Reed Canarygrass Series*
242.2 Northeastern Maritime (Coastal) Marshland
242.21 Saltgrass Series*
242.3 Plains Interior Marshland (fig. 83)
242.31 Rush Series*
242.32 Bur-reed Series*
242.33 Cattail Series*
242.34 Bulrush Series*
242.4 Rocky Mountain Montane Marshland
242.41 Rush Series*
242.5 Great Basin Interior Marshland
242.51 Rush Series*
242.52 Saltgrass Series*
242.6 Sierran—Cascade Montane Marshland
242.61 Rush Series*
242.7 Pacific Coastal (Oregonian) Interior Marshland
242.71 Rush Series*
242.8 Pacific Coastal (Oregonian) Maritime Marshland
242.81 Saltgrass Series*
242.82 Glasswort Series*

243 Warm Temperate Marshlands
243.1 Southeastern Interior Marshland
243.11 Cattail Series*
243.2 Southeastern Maritime Marshland (fig. 84)
243.21 Saltmarshgrass Series*
243.3 Chihuahuan Interior Marshland
243.31 Saltgrass Series*
243.4 Mohavian Interior Marshland
243.41 Rush Series*
243.42 Saltgrass Series*
243.5 Madrean Marshland
243.51 Rush Series*
243.6 Californian Interior Marshland
243.61 Cattail Series*
243.7 Californian Maritime Marshland
243.71 Cordgrass Series*
243.72 Glasswort Series*

244 Tropical—Subtropical Marshland
244.1 Caribbean Interior Marshland
244.11 Cattail Series*
244.12 Giant Reed Series*
244.13 Sawgrass Series*
244.2 Caribbean Maritime Marshland
244.21 Saltgrass Series*
244.3 Tamaulipan Interior Marshland
244.31 Cattail Series*
244.32 Giant Reed Series*
244.4 Gulf Coast Maritime Marshland
244.41 Saltgrass Series*
244.5 Sinaloan Interior Marshland
244.51 Cattail Series*
244.6 Sinaloan Maritime Marshland
244.61 Glasswort Series*
244.7 Sonoran Interior Marshland (fig. 85)
244.71 Cattail Series*
244.72 Giant Reed Series*
244.73 Bulrush Series*
244.74 Threesquare Series*
244.8 Sonoran Maritime Marshland
244.81 Saltgrass Series*
244.82 Glasswort Series*

250 Strand Formation
251 Arctic—Boreal Strands
251.1 Polar Maritime Strand***
251.2 Greenlandian Strand***
251.3 Alaskan Maritime Strand***
251.4 Canadian Interior (Stream and Lake) Strand***
251.5 Canadian Maritime Strand***
251.6 Adirondack—Appalachian Alpine and Subalpine Stream and Lake Strand***
251.7 Rocky Mountain Alpine and Subalpine Stream and Lake Strand***
251.8 Sierran—Cascade Alpine and Subalpine Stream and Lake Strand***

****Our incomplete knowledge of these biotic communities precludes presentation of representative fifth (series) level examples.*

252 Cold Temperate Strands
252.1 Northeastern Interior (Stream and Lake) Strand***
252.2 Northeastern Maritime Strand
252.21 Sandreed Series*
252.3 Plains Interior (Stream and Lake) Strand
252.31 Annual Series*
252.4 Rocky Mountain Montane Stream and Lake Strand
252.41 Annual Series*
252.5 Great Basin Interior Strand
252.51 Annual Series*
252.6 Sierran—Cascade Interior Strand
252.61 Annual Series*
252.7 Pacific Coastal (Oregonian) Interior Strand***
252.8 Pacific Coastal (Oregonian) Maritime Strand (fig. 86)
252.81 Sandreed Series*

253 Warm Temperate Strands
253.1 Southeastern Interior Strand***
253.2 Southeastern Maritime Strand*** (fig. 87)
253.3 Chihuahuan Interior Strand
253.31 Annual Series*
253.4 Mohavian Interior Strand
253.41 Annual Series*
253.42 Mixed Scrub Series*
253.5 Madrean Stream and Lake Strand
253.51 Annual Series*
253.6 Californian Interior Strand
253.61 Annual Series*
253.7 Californian Maritime Strand
253.71 Mixed Scrub Series*
253.72 Sea-grass Series*
253.73 Green Algae Series*
253.74 Brown Algae Series*
253.75 Red Algae Series*

254 Tropical—Subtropical Strands
254.1 Caribbean Interior Strand***
254.2 Caribbean Maritime Strand***
254.3 Tamaulipan Interior Strand***
254.4 Gulf Coast (Tamaulipan) Maritime Strand***
254.5 Sinaloan Interior Strand
254.51 Annual Series*
254.6 Sinaloan Maritime Strand
254.61 Mixed Scrub Series*
254.7 Sonoran Interior Strand (fig. 88)
254.71 Mixed Scrub Series*
254.72 Annual Series*
254.8 Sonoran Maritime Strand (fig. 89)
254.81 Mixed Scrub Series*

260 Submergent Vegetation
261 Arctic—Boreal Submergents
261.1 Polar Marine Submergents
261.11 Phytoplankton Series*
261.2 Greenlandian Inland Submergents
261.21 Phytoplankton Series*
261.3 Alaskan Marine Submergents
261.31 Phytoplankton Series*
261.4 Canadian Inland Submergents
261.41 Phytoplankton Series*
261.5 Canadian Marine Submergents
261.51 Phytoplankton Series*
261.6 Adirondack—Appalachian Alpine and Subalpine Submergents
261.61 Phytoplankton Series*
261.7 Rocky Mountain Alpine and Subalpine Submergents
261.71 Phytoplankton Series*
261.72 Pondweed Series*
261.8 Sierran—Cascade Alpine and Subalpine Submergents (fig. 90)
261.81 Phytoplankton Series*
261.82 Pondweed Series*

262 Cold Temperate Submergents
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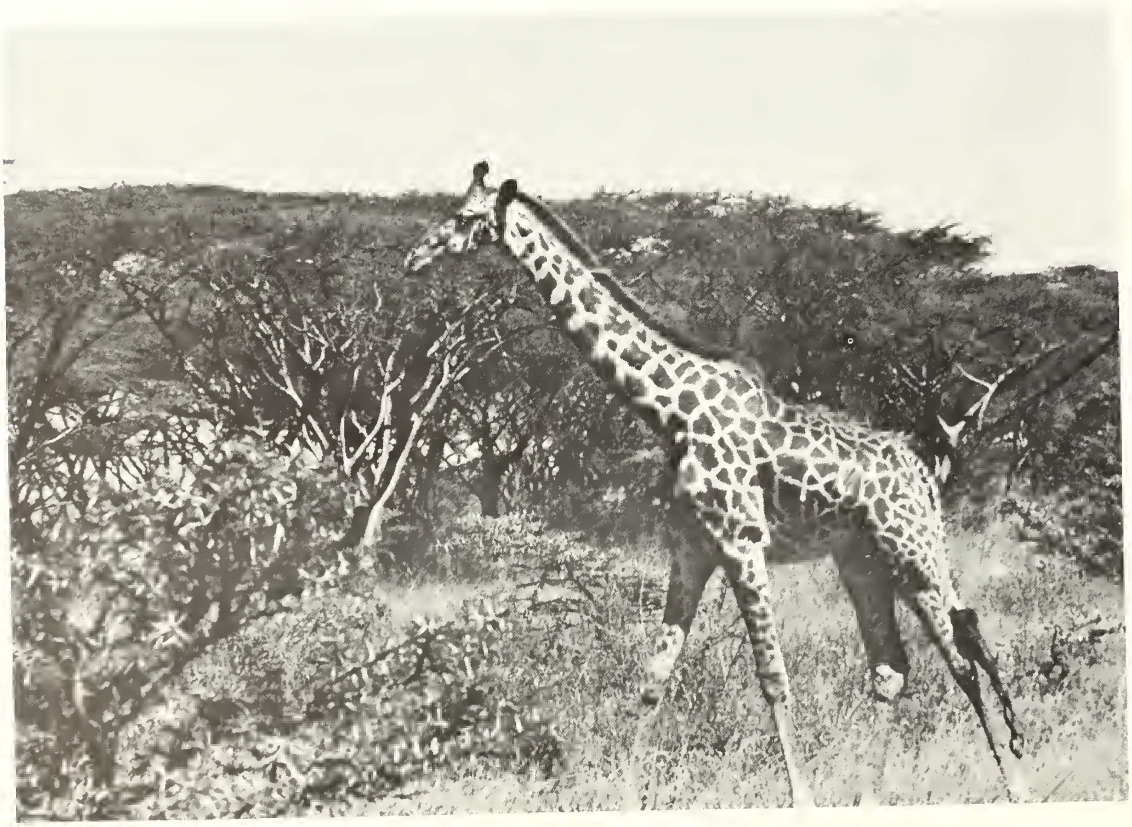

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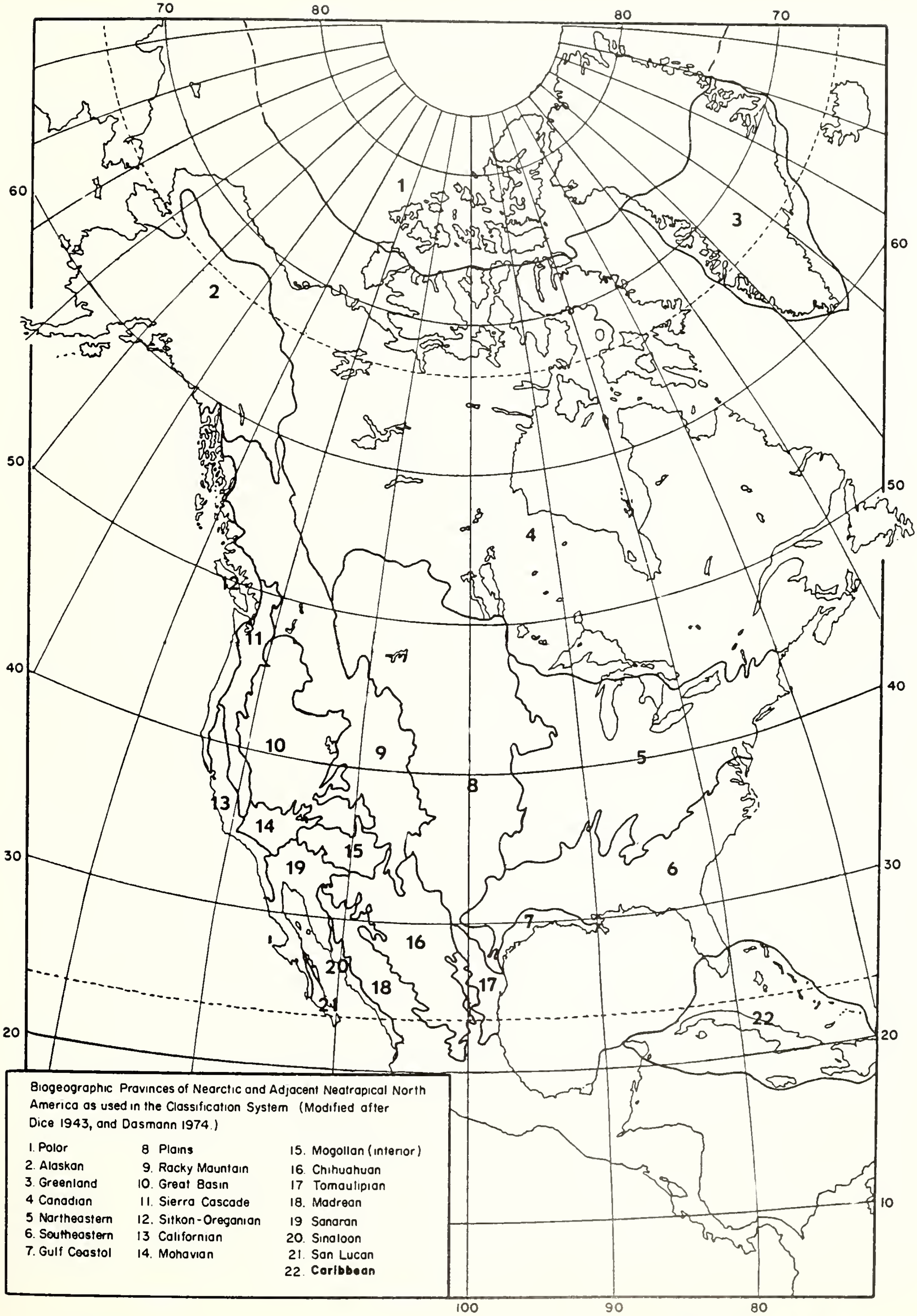

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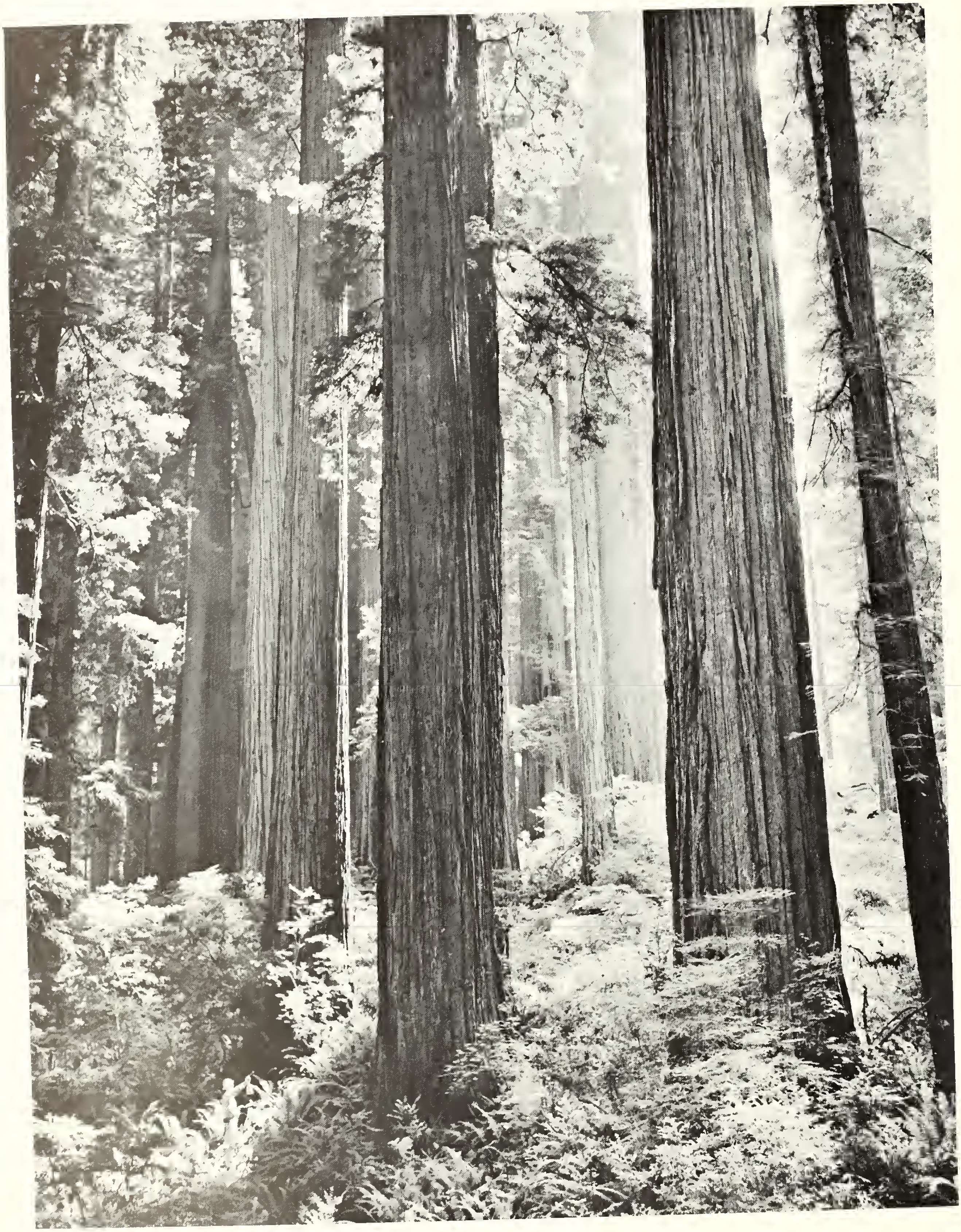

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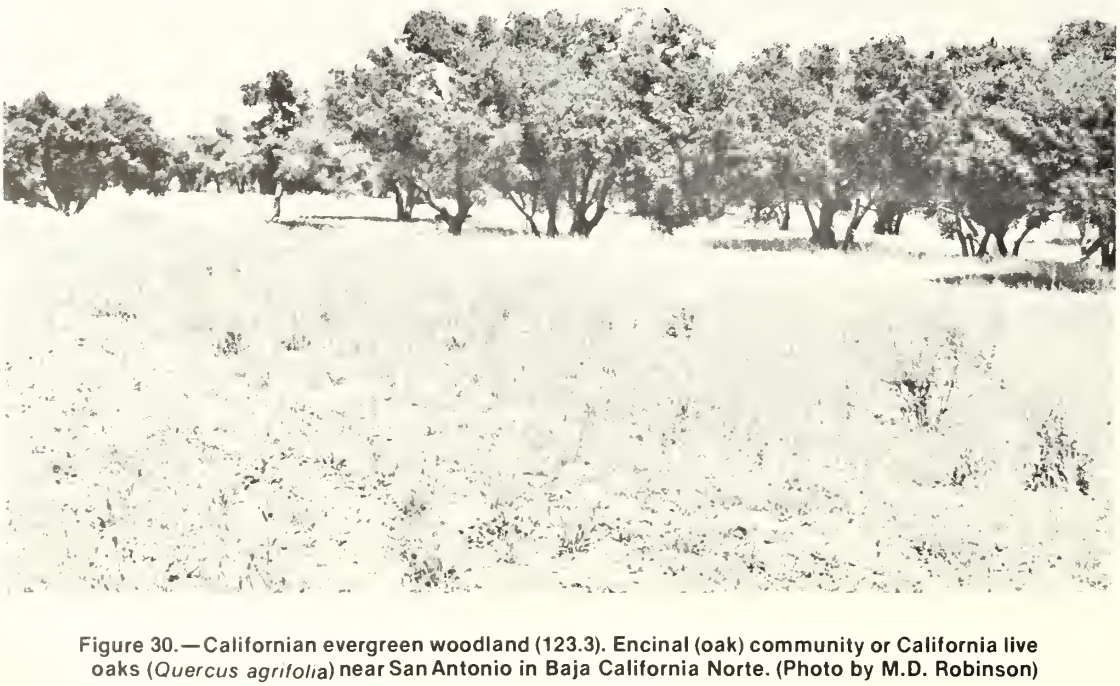

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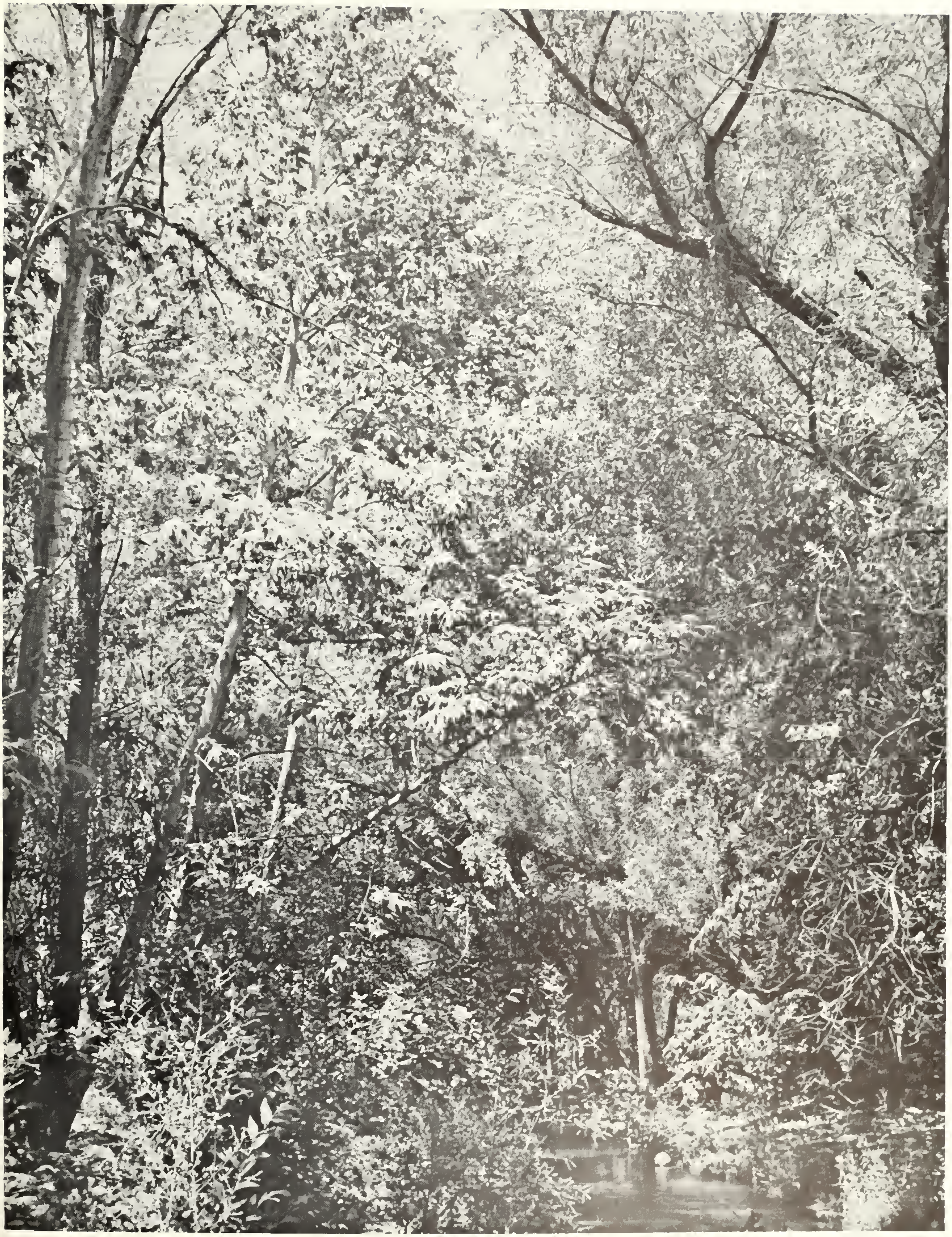

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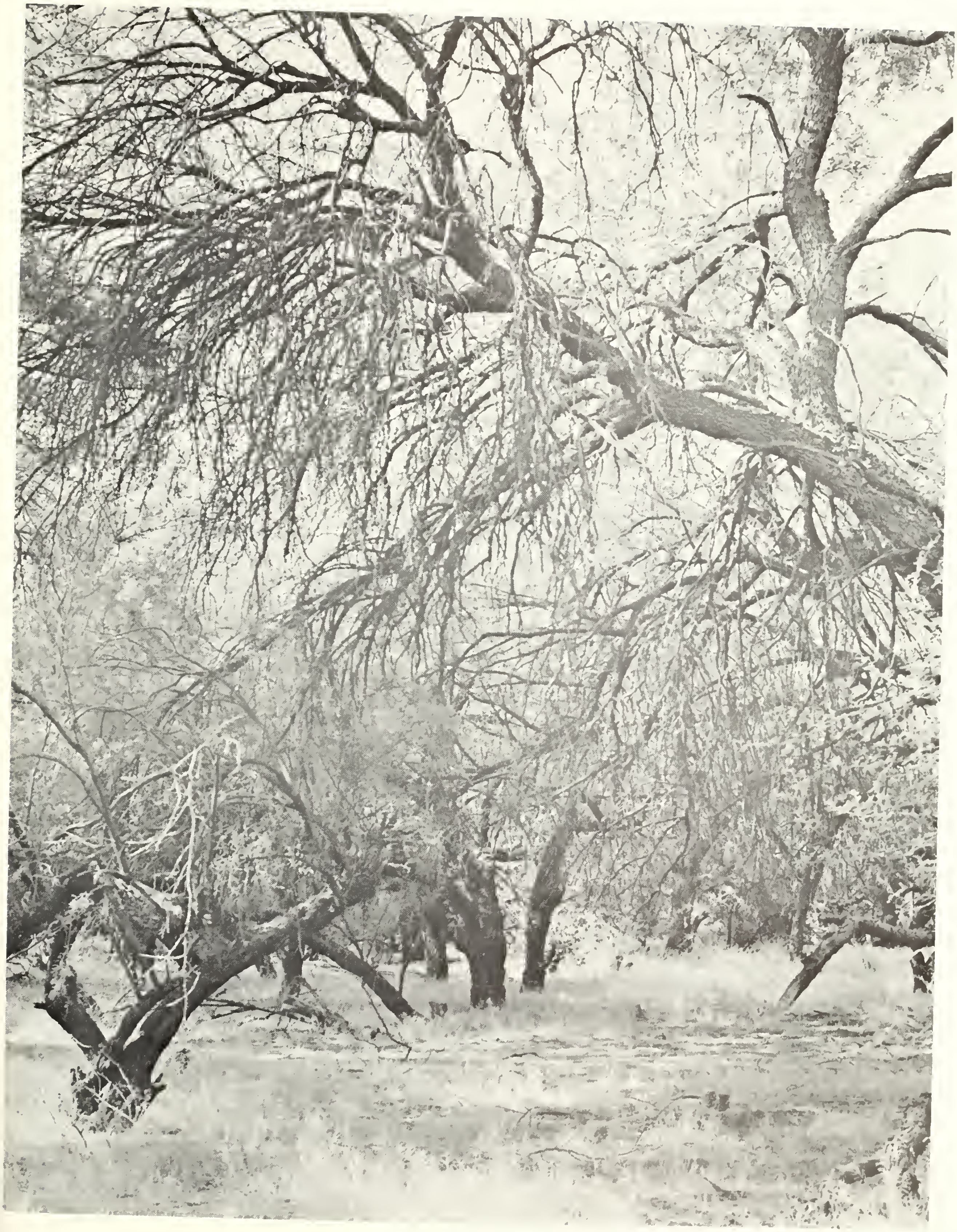

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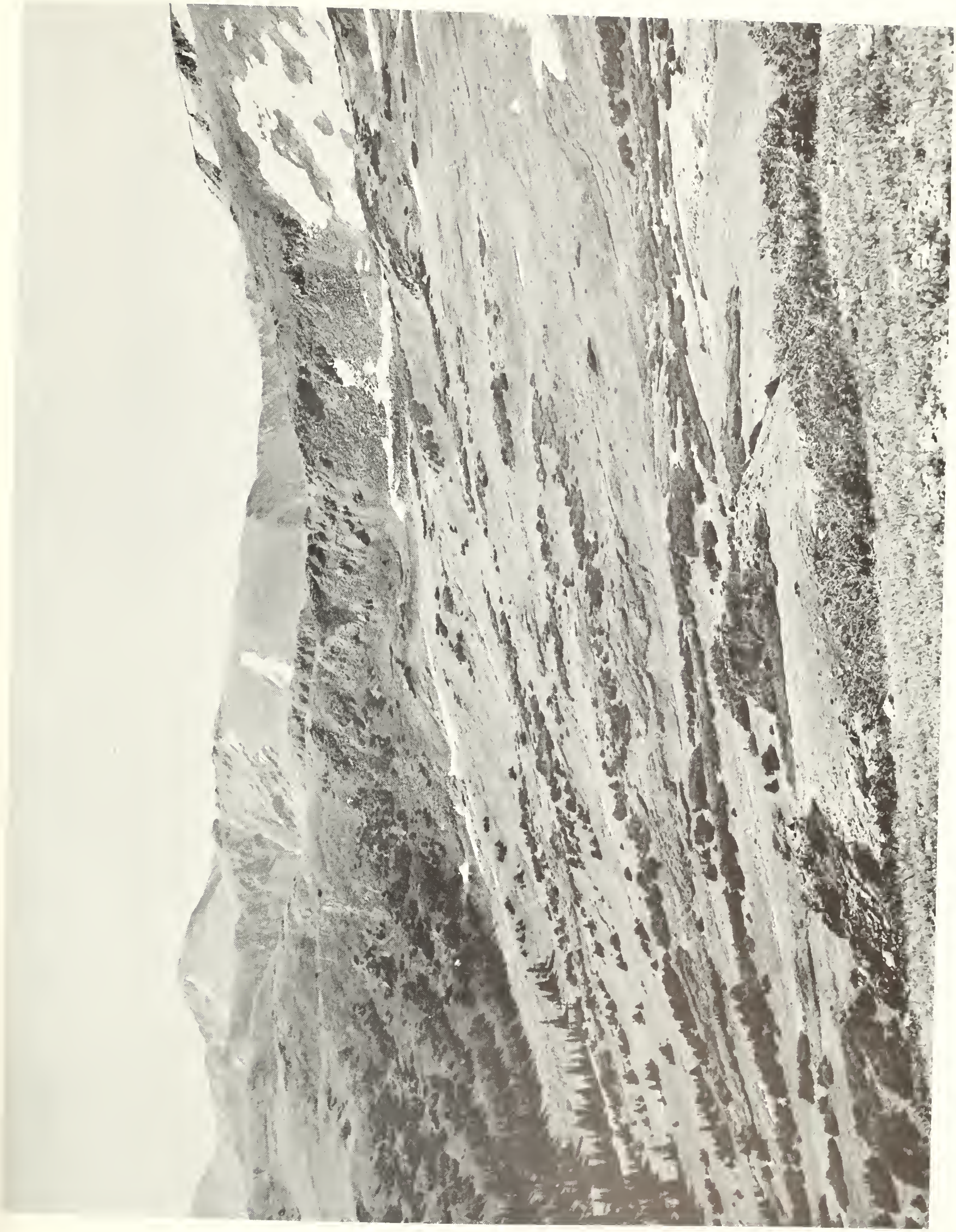

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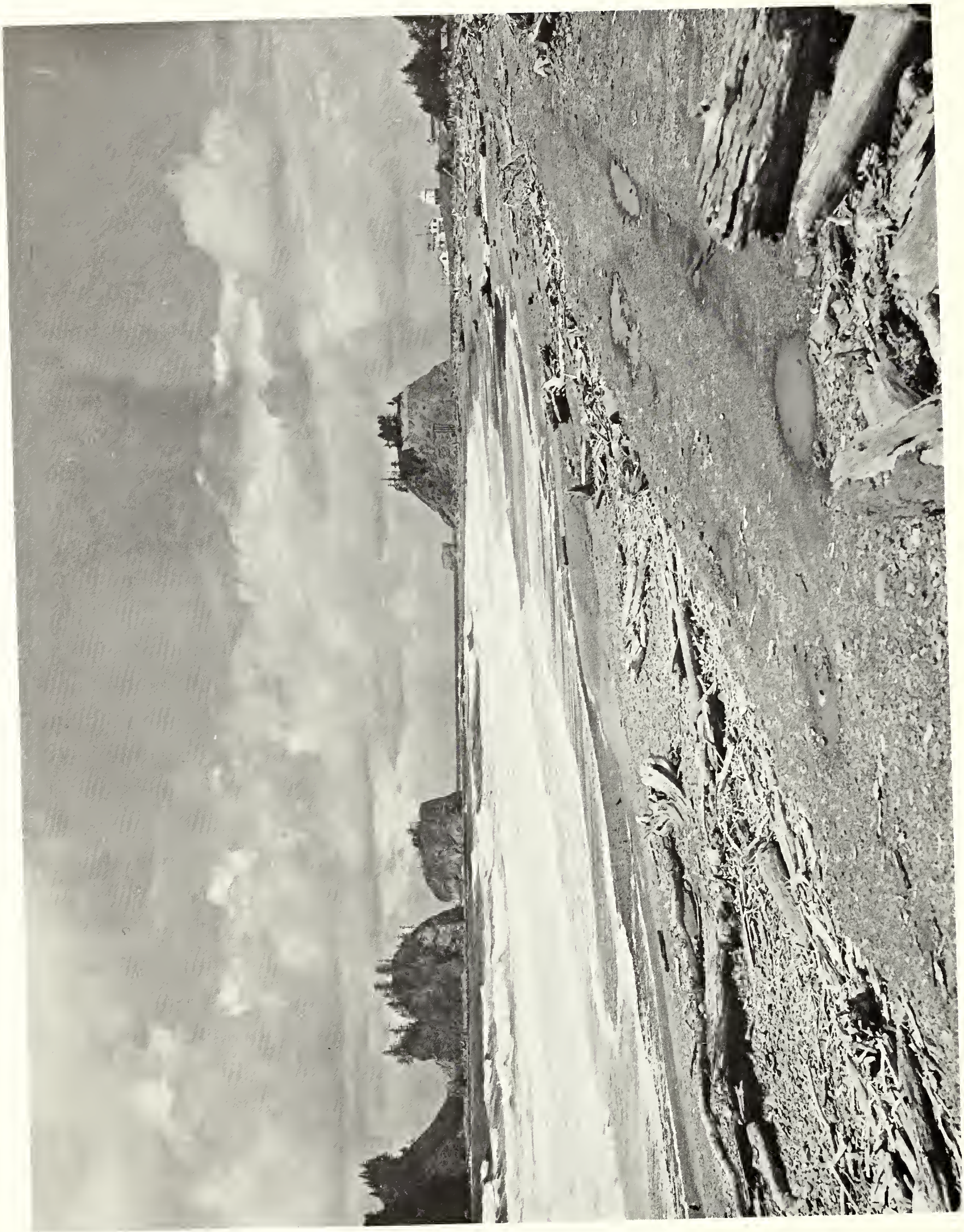

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Brown, David E., Charles H. Lowe, and Charles P. Pase. 1980. A digitized systematic classification for ecosystems with an illustrated summary of the natural vegetation of North America. USDA Forest Service General Technical Report RM-73, 93 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

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Keywords: digitized system classification, North American vegetation, ecosystems

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Southwest

Great Plains

U.S. Department of Agriculture
Forest Service

Rocky Mountain Forest and Range Experiment Station

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Texas Panhandle Pheasants:

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Jay Custer
Mike Owen

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Texas Panhandle Pheasants:
Their History, Habitat Needs, Habitat Development Opportunities, and Future[1]

Fred S. Guthery, Assistant Professor
Jay Custer, Research Assistant
and
Mike Owen, Research Assistant

Texas Tech University
Lubbock, Texas

Abstract

Pheasants *(Phasianus colchicus)* colonized the Texas Panhandle in the late 1930's. Panhandle habitat is deficient in travel lanes, secure nesting cover, and over-winter cover. The high value of cropland limits habitat development, but cover plantings may be feasible on idle areas. Aquifer depletion will probably decrease pheasant populations in the future.

[1]Research reported here was funded jointly by the Rocky Mountain Forest and Range Experiment Station and Texas Tech University. The Station's headquarters is at Fort Collins, in cooperation with Colorado State University. Supervision was provided by Fred A. Stormer, Project Leader at the Station's Research Work Unit at Lubbock, in cooperation with Texas Tech University.

Texas Panhandle Pheasants: Their History, Habitat Needs, Habitat Development Opportunities, and Future

Fred S. Guthery, Jay Custer, and Mike Owen

Management Implications

The most severe habitat deficiencies of pheasants *(Phasianus colchicus)* in the Texas Panhandle, as in many portions of their range, are secure nesting cover, over-winter cover, and travel lanes. Habitat development is infeasible on croplands because of the substantial revenue that would be lost by taking these lands out of production. However, habitat development opportunities exist on playa lake basins, roadsides, dry corners associated with center-pivot sprinkler systems, and irrigation tail-water recovery pits. These areas, if undisturbed, would provide needed cover, but the natural vegetation communities that develop may be unacceptable to farmers. Thus, herbaceous plants that are attractive and able to outcompete "weeds" must be established. Such habitat developments would beautify the landscape, save energy (because control of weeds would be unnecessary), and benefit both game and nongame wildlife in the Texas Panhandle.

Introduction

Pheasants, Asian natives first established in Oregon in the 1880's (Edminster 1954), occur latitudinally from the Gulf Coast of Texas (Evans 1977) to the southern provinces of Canada, and longitudinally from the Atlantic Ocean to the Pacific Ocean (Johnsgard 1975). Their history, ecology, and management are well documented throughout most of this range. The birds have received little research attention in the Texas Panhandle.

Purposes of this study were to (1) consolidate available information on history; (2) determine habitat deficiencies; (3) determine habitat development opportunities consistent with social, economic, ecological, and agricultural constraints; and (4) assess the species' future in the Texas Panhandle.

Establishment and Range Expansion

The first recorded liberation of pheasants in Texas occurred along the Gulf Coast in 1933-1934 (Holloran and Howard 1956). About 400 birds were released on what is now Aransas National Wildlife Refuge, but none was seen after January 1939.

Yeager et al. (1956) reported that "the last state in the arid Southwest to initiate pheasant stocking was Texas, in 1939." This method of establishment conflicts with that described by Jones and Felts (1950), who wrote that pheasants drifted into Texas from Oklahoma or Kansas via Oklahoma beginning in 1939 or 1940. Evans (1977) indicated that "pheasants immigrated into the High Plains of Texas from Oklahoma during the 1940's." Parsons (1973) considered Colorado a possible source of Panhandle pheasants.

Oklahoma is the most likely source of Texas' pheasants for two reasons. First, massive releases occurred in Oklahoma beginning about 1910 (Hanson 1946). Second, ingress from Kansas or Colorado, although not impossible, seems implausible. Although it is only 61 km across the Oklahoma Panhandle from Colorado or Kansas to Texas, stable, huntable pheasant populations were found only in northern portions of Colorado (Yeager et al. 1956) and Kansas[2] in 1925-1930. To accept the hypothesis that birds from these states colonized Texas, we must assume they dispersed 300 km or more in 10-15 years. Ingress from New Mexico is unlikely, because the first successful introduction occurred in the southwestern part of that state in 1929 (Campbell 1976).

Though lacking proof, we suspect that private, unrecorded releases played a role in establishment of Panhandle pheasants, as was the case in Oklahoma and Kansas. In Oklahoma, citizens may have planted

[2]*Norman, Jim. 1970. Sketches from the history of pheasants in Kansas. 13th annual meeting, Midwest Pheasant Council. [Hays, Kans., April 6-10, 1970].*

more birds than were released by the Fish and Game Department (Hanson 1946). In Kansas private liberations beginning in the 1880's (Kimball et al. 1956) resulted in nucleus populations by 1904.[2]

About 10 years after their arrival in the Panhandle, pheasants occupied portions of at least 18 counties (fig. 1) and occurred primarily along waterways (Jones and Felts 1950). Release of countless birds by private individuals in nearly every Panhandle county aided range expansion and probably explains how pheasants crossed the Canadian River breaks, a broad expanse of rangeland considered a barrier to southward dispersal (Evans 1977). Populations of 1950 were described by Jones and Felts as intermittent, drifting, and spotted in distribution.

By the early 1970's there were pheasants in at least 24 Panhandle counties (fig. 2), though huntable populations existed in only 18 counties (Parsons 1973). Besides probable natural dispersal, releases by landowners, sportsmen, civic groups, and government agencies continued to expand pheasant range. From 1960 to 1973, the U.S. Soil Conservation Service distributed pheasants to landowners for release in Bailey, Crosby, Hale, and Terry counties.[3] The Texas Parks and Wildlife Department (TPWD) began liberating white-winged pheasants (*P. c. bianci*) in 1967 (Evans 1977) in Bailey and Hale counties where 100-200 birds were planted annually until 1969.[4] More recently, Farm Bureau members in Swisher County released pheasants, and 4-H Clubs and Future Farmers of America sold birds for liberation in Gaines County.

Pheasants occupied portions of at least 33 counties in 1977 (fig. 3). (See appendix A for methods used to determine distribution and relative density.) Whether populations in all of these counties are self-sustaining is unknown. Recent expansion of the range of Panhandle pheasants also has been caused by introductions. The TPWD has released some 2,100 birds in southern Gray and western Carson counties since 1974.[4]

Based on Pittman-Robertson reports filed at TPWD headquarters in Austin, Tex., management of Panhandle pheasants has consisted of liberations, counts along roadsides, establishing harvest regulations, and monitoring harvest. The first hunting season was held

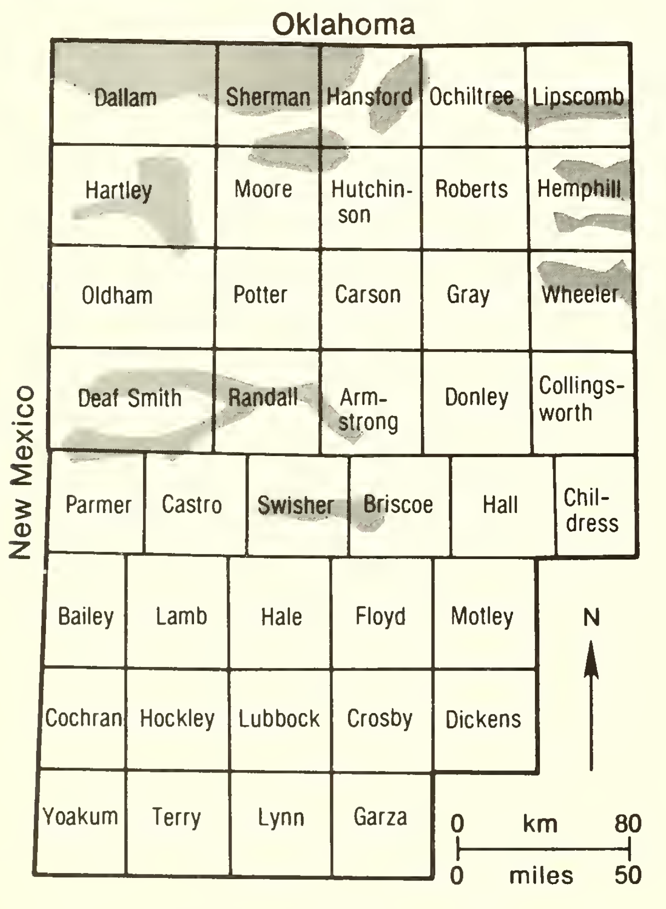

Figure 1.—Minimum distribution of pheasants in the Texas Panhandle in 1950 (Jones and Felts 1950).

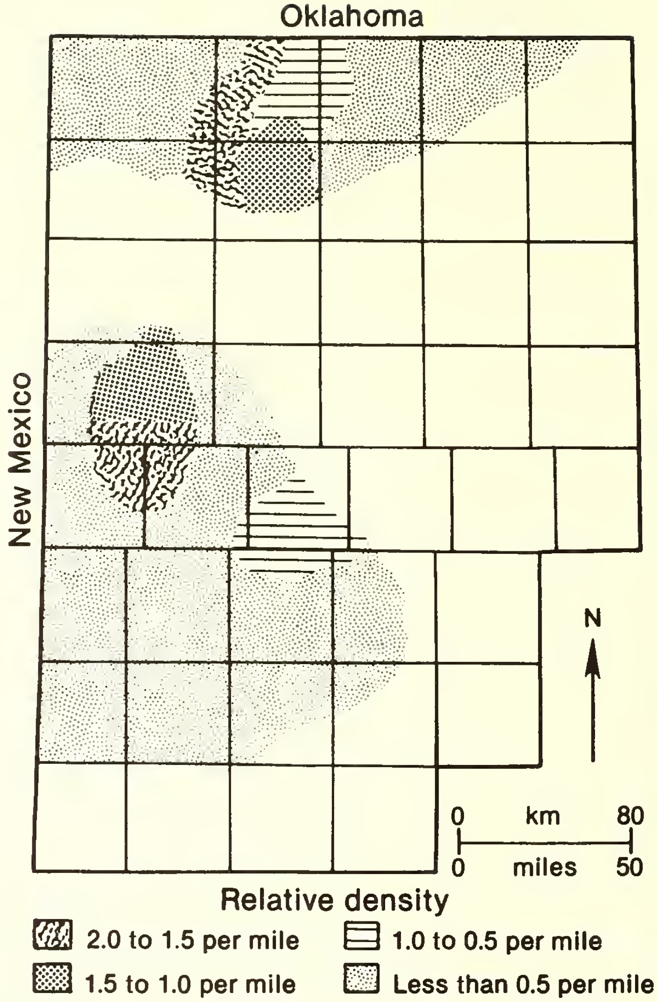

Figure 2.—Minimum distribution of pheasants in the Texas Panhandle in the early 1970's (Parsons 1973).

[3] *Unless otherwise cited, data are from the questionnaire survey shown in appendix A.*

[4] *Dick DeArment, personal communication, Texas Parks and Wildlife Department, Wheeler, Tex.*

in Dallam County in 1958 (see tabulation below) with a bag limit of two cocks per day and four in possession, which has remained the same to present. Counts along roadsides, initiated in 1960, were too few to judge temporal trends in abundance until 1972 when 15-19 transects were run. Fall counts along roadsides suggest gradually increasing populations from 1972 through 1976. The proportion of juvenile cocks in the hunting bag ranged between 12% and 70% during 1959 through 1973 and averaged 46.7% ± 4.8%. By comparison, this proportion averaged 71% in northwest Kansas during 1963 through 1967 (Norman 1971). Estimated legal kill was 24,000 cocks in 1976.[5]

Year	December dates	Counties
1958	13-14/20-21	Dallam
1959	12-13/19-20	Dallam
1960	10-11/17-18	Dallam, Sherman, Moore, Oldham
1961	9-10/16-17	Panhandle Regulatory District, 32 counties
1962	1-7	Northern two tiers
1963	1-7	Northern two tiers
1964	1-7	Panhandle Regulatory District, 33 counties
1965	1-7	33
1966	1-7	33
1967	1-7	33
1968	14-22	33
1969	13-21	33
1970	12-20	33
1971	11-19	33
1972	9-17	33
1973	8-23	33
1974	14-29	33
1975	13-28	33
1976	11-26	33
1977	10-25	33 + 8-day season in Terry County

Panhandle Habitat

Physical Environment

Two land resource areas, the High and Rolling Plains (fig. 4), comprise pheasant range in the Texas Panhandle. The Rolling Plains range in elevation from 330 to 1,000 m; have rolling topography with entrenched stream valleys; and have neutral to calcareous sandy loams, clay loams, and clays over loamy to clayey subsoils (Godfrey et al. [n.d.]). Because about 75% of the Rolling Plains currently consists of shortgrass range, this region is of marginal value to pheasants. The High Plains range in elevation from 1,000 to 1,330 m; have nearly level, practically undissected topography dotted with thousands of playa lake basins; and have mostly deep, neutral to calcareous clay loams, sandy loams, and sands over loamy to clayey subsoils.

[5]*News release from Texas Parks and Wildlife Department, Austin.*

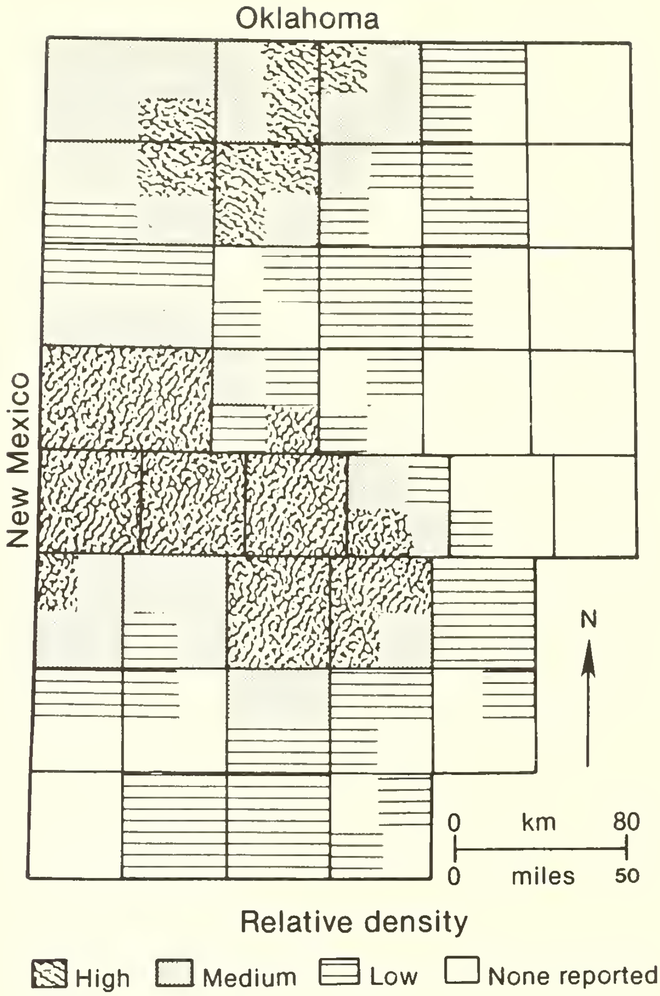

Figure 3.—Minimum distribution of pheasants in the Texas Panhandle in 1977 based on a questionnaire survey.

Climate of the Texas Panhandle is classified as midlatitude semiarid (Critchfield 1966). Mean annual precipitation (41-56 cm) and mean length of frost-free period (180-230 days) increase from west to east (Godfrey et al. 1973). Rainfall usually is low (10-20% of total) during November through March with peaks in April-May and September-October (Gould 1969, A. H. Belo Corporation 1975). The Panhandle has periodic droughts, annual snowfall averages 9-35 cm, and number of days with temperatures below freezing averages 50-110. Mean annual temperature is about 16° C.

Land Use and Habitat Deficiencies

Pheasants require cropland, grassland, and woody or rank herbaceous vegetation (Edminster 1954). Cropland provides food, as 70% or more of the adult pheasant diet typically is composed of grains. Corn is the most important crop, followed by the small grains. The type grassland described by Edminster is moderately dense herbaceous vegetation, composed either of grasses, forbs (e.g., alfalfa), or grass-forb mixtures.

The most important function of this type is nesting cover. Woody vegetation, such as windbreaks, orchards, woodlots, and bottomland trees, provides shelter during extremes of both heat and cold. Rank herbaceous vegetation, particularly cattails (*Typha* spp.) and associated wetland plants, also provides shelter.

Optimum land use patterns for pheasants include more than 50% of an area devoted to grains with 50% of the grain land in seed corn (Edminster 1954). Between 5% and 20% of the area should consist of mottes, woody ravines, woodlots, roadsides, ditchbanks, fencelines, and other odd areas forming a network of travel lanes. The balance should be in grass, legumes, or grass-legume mixtures, preferably harvested for seed. The minimum size for a pheasant management unit is about 30 km² (Gates and Hale 1974).

Baxter and Wolfe [n.d.] were more specific in recommendations of optimum land use patterns for pheasants in Nebraska. They suggested that a management unit consist of 42% corn or sorghum, 36% wheat, 14% grassland, 6% idle areas, and 2% alfalfa.

Texas Panhandle strata (fig. 4) provide low-quality pheasant habitat when compared to optimum patterns

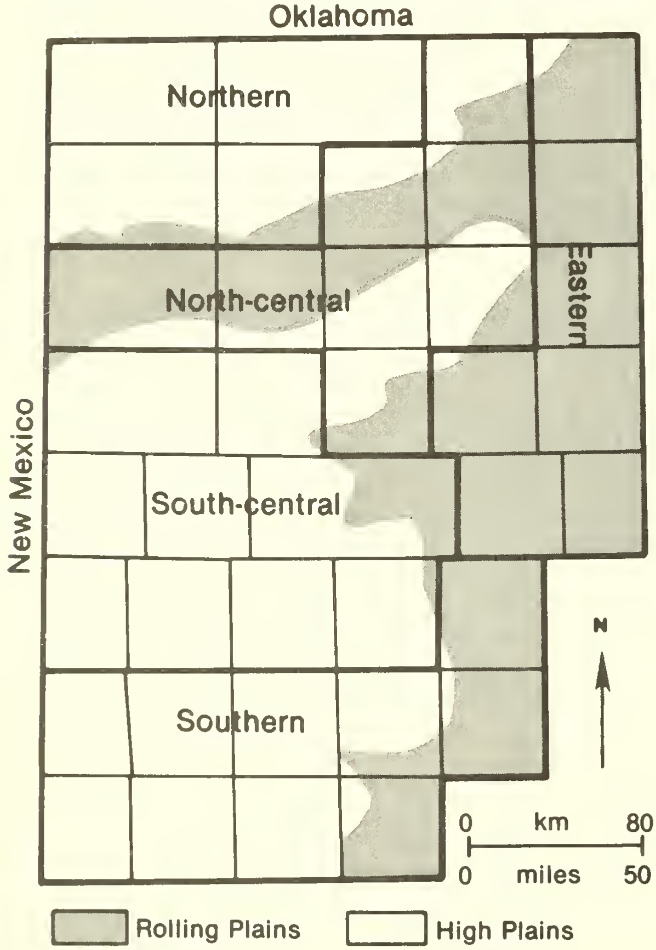

Figure 4.—Land resource areas of the Texas Panhandle and arbitrary stratification of counties based on relative pheasant density and geographical proximity.

described by Edminster (1954) and Baxter and Wolfe [n.d.]. The southern stratum is particularly deficient because of high proportions of cotton and clean roadsides (tables 1 and 2). (See appendix B for methods used in land use and habitat surveys.) Rangeland and cotton comprise more than 70% of the eastern stratum. Our survey underestimated the proportion of rangeland in the north-central stratum because we avoided extensive rangeland areas in establishing transects. The northern and south-central strata have land use patterns providing the best pheasant habitat available in the High Plains. The south-central stratum is best overall because land use patterns are more diverse, irrigation (indexed by number of pumps per 10 km) is most highly developed, and playa lake basins are more abundant. All strata were deficient in idle (odd) areas and travel lanes. Optimum occurrence of travel lanes is probably about 25 per 10 km, but Panhandle areas had less than 11 travel lanes per 10 km.

A lack of secure nesting cover limits pheasant populations throughout their range (MacMullan 1961), including Texas (Parsons 1976). Although crops supply about 1.5 million ha of potential nesting cover (table 3), harvest and planting timetables in the Panhandle are inimical to nesting success (fig. 5). Hatching dates in Nebraska, which presumably would be similar to those in Texas, range from late April to mid-August with a peak in June (Baxter and Wolfe 1973), when harvest of small grains is peaking in Texas and other crops are being planted.

Playa lake basins, either modified (trenched to concentrate water and reduce evaporation) or unmodified, provide most noncultivated nesting habitat in the Panhandle. Estimates place the number of basins in this region between 17,000 (Lehman 1972) and 30,000 (Ward and Huddleston 1972). Reeves and Perry (1967) estimated 900-1,000 depressions occur per normal county area (2,300 km²).

Odd areas and travel lanes that could serve as nesting habitat are notably absent in the Texas Panhandle (table 2). Roadsides in areas of dryland farming support sparse cover, even if they are not bladed, disked, or mowed. Roadsides in irrigated areas provide more cover, including Johnsongrass (*Sorghum halepense*), annual sunflower (*Helianthus annus*), thistle (*Salsola kali*), red sprangletop (*Leptochloa filiformis*), and other species, but control of this vegetation is intense. Odd areas, extremely sparse, consist mainly of small, abandoned farmsteads. The flat topography of the High Plains precludes areas that are too steep to farm. Fencelines are scattered widely, though it is common practice to graze livestock on stubble and sprouting cereals by stringing temporary electric fences.

Rangeland occupies a large portion of the Panhandle (table 1) but provides nesting cover of poor quality. Most areas are grazed heavily, resulting in vegetation lower than the 25-cm limit required by nesting hens (Gates and Hale 1975).

Over-winter cover, like nesting habitat, is deficient in the Texas Panhandle (Parsons 1976). Crops provide

Table 1.—Estimated percentages of Texas Panhandle strata allocated to various land uses, mid-August 1978. Percentages are based on 240 sample points per stratum

Land use	Panhandle stratum: Northern	South-central	North-central	Southern	Eastern
Cotton	(1)[1]	19	0	74	23
Sorghum	18	8	20	10	5
Corn	10	18	3	(1)	0
Soybeans	(1)	4	0	(1)	0
Small grains	3	(1)	2	0	(1)
Hay	1	(1)	0	0	0
Vegetables and sugar beets	(1)	2	0	0	0
Rangeland					
Shortgrass range	17	12	21	3	43
Shin oak range	0	0	0	(1)	7
Tame pasture[2]	(1)	(1)	0	0	5
Fallow or tilled[3]	45	36	55	8	15
Other	3	(1)	(1)	1	2

[1] *Less than 0.1.*
[2] *Includes seeded rangeland.*
[3] *Over 90% of these areas were disked or plowed small grain fields.*

Table 2.—Habitat features for pheasants by Texas Panhandle strata, mid-August 1978

Habitat feature	Panhandle stratum: Northern	South-central	North-central	Southern	Eastern
	Percent				
Percentage of roadsides bladed, disked, or mowed[1]	79	69	73	96	69
	Number per 10 km				
Travel lanes	4.0	6.7	10.6	3.5	0.8
Windbreaks, mottes, and other woody shelters	6	2.9	1.7	3.0	(2)
Fenced playas	7	2.5	1.4	1.8	1
Unfenced playas	2	8	1	2	0
Weedy tail-water pits	6	4	1.1	0	0
Clean tail-water pits	9	5	6	2	(3)
Topographic draws	3	4	1.7	2	
Irrigation pumps	3.2	7.6	2.2	6.0	(3)
Odd areas	1.8	2.1	3.2	1.4	1

[1] *Roadside vegetation less than 30 cm tall.*
[2] *Many.*
[3] *Less than 1.*

Table 3.—Agricultural nesting habitat (thousands of hectares) available to pheasants in the Texas Panhandle[1]

Panhandle stratum	Small grains	Hay	Soybeans	Total
Northern	288	6	4	298
South-central	518	14	51	583
North-central	326	10	3	339
Southern	121	8	6	135
Eastern	174	17	(2)	191
Total	1,427	55	64	1,546

[1] *Data are from bulletins published jointly by the Texas Crop and Livestock Reporting Service and the U.S. Department of Agriculture.*
[2] *Less than 1.*

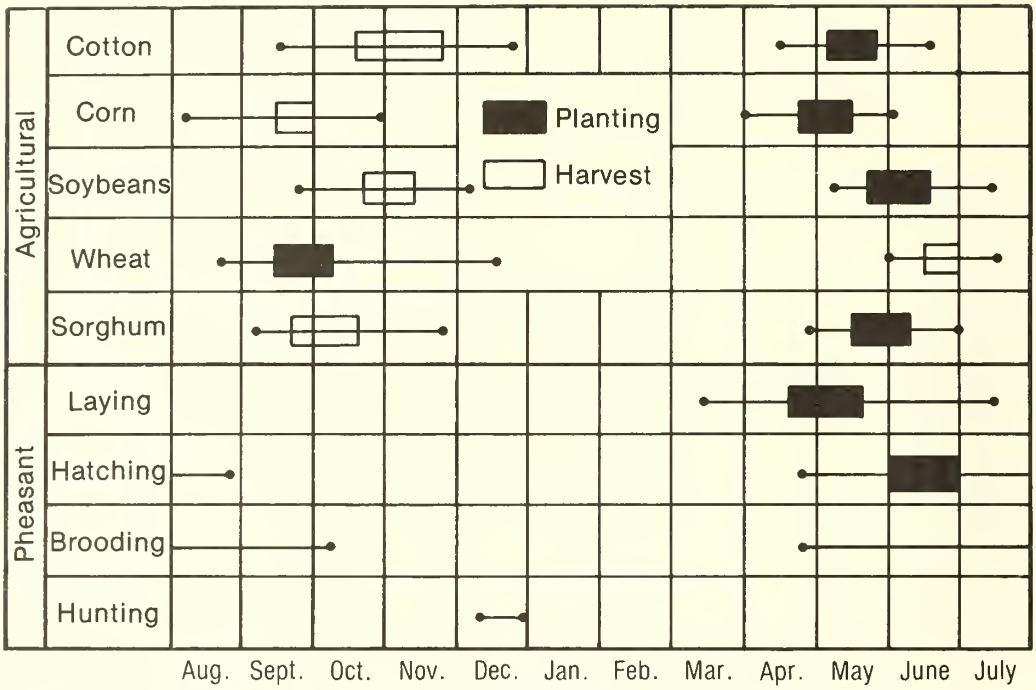

Figure 5.—Comparison of agricultural and presumed pheasant phenology on the High and Rolling Plains of Texas. Rectangles represent the approximate time span during which the middle 50% of the activity occurs.

little cover during late fall, winter, and spring because most have been harvested and fields are being prepared for planting (fig. 5). Windbreaks, mottes, and other woody shelters are sparse in four of five Panhandle strata (table 2). Thus, playa basins harboring rank herbaceous vegetation, tail-water pits with weedy perimeters, some roadsides, and abandoned farmsteads supply most overwinter cover.

Habitat Development Opportunities

We are proposing habitat development as opposed to habitat management. Development means creating habitat where either no habitat or marginal habitat had existed before. Thus, practices such as minimum tillage or delayed tillage of stubble which would benefit pheasants while costing landowners little or nothing are largely ignored. We recognize the value of such practices, but creation of stable habitat is the more pressing need of Panhandle pheasants.

The specific programs proposed appear to be (1) ecologically sound in that they would provide needed habitat (nesting cover, over-winter cover, and travel lanes) for Panhandle pheasants, (2) socially acceptable in that they would add to the diversity and esthetic appeal in landscapes, and (3) compatible with agriculture in that they can be incorporated into the existing agricultural system with little or no loss of productivity.

Playa Basin Developments

Without playas the Texas Panhandle would support substantially fewer pheasants. These depressions provide virtually all over-winter cover, serve as nesting and brooding cover, and supply foods such as barnyardgrass (*Echinochloa crusgalli*) and smartweeds (*Polygonum* spp.). Also, playas of moderate to large size cannot be farmed. Landowners likely would welcome the opportunity to turn some profit from these areas through leasing. Playa development is needed because about 75% of the playas in the northwest and south-central strata were classified as marginal pheasant habitat. Listed below are options for playa basins.

Small (<1 ha) basins on cropland (fig. 6).—Farmers expend time and fossil energy controlling weeds in such basins. An alternative approach is to establish an acceptable plant, perhaps alfalfa, in the depressions to simultaneously control weeds and provide cover for pheasants.

Medium-sized (5-15 ha) basins (fig. 7).—Outer zones of medium-sized playas may or may not be farmed in any given year, depending upon amount of rainfall. Average net returns from crops on such areas undoubtedly are low. Over the long run, farmers might save money by planting outer zones subject to periodic inundation to a species that both controls weeds and provides cover for pheasants. Leasing peripheral zones of playas, if necessary, should be less expensive than leasing stable cropland. Revenue losses from removal of grazing must be figured into the lease price.

Grazed basins (fig. 8).—Removal of grazing from any playa basin will improve pheasant habitat. An alternate plan is to begin grazing after the peak of spring hatch and end grazing early enough in the summer to

Figure 6.—Small, shallow playa lake basins on cropland, usually farmed or disked for weed control, offer opportunities for development of pheasant cover.

Figure 7.—Margins of medium-sized playa lake basins which cannot be farmed offer opportunities for development of pheasant cover.

ensure production of residual cover for next season's nesting.

Roadside Development

Roadsides offer vast opportunity for management in the Texas Panhandle because most are bladed, disked, or mowed (table 2). Distinct social, economic, and biological advantages are associated with management of roadside vegetation. Savings in fossil fuels would be substantial if roadsides were planted to a species that eliminated the need for control of noxious vegetation. Expenditure of state and county tax dollars would decrease in proportion to the amount of roadsides not requiring maintenance. Control of roadside vegetation is expensive. Joselyn et al. (1968) cited these figures for Illinois in 1963: "interstate highways $617 per km, and state highways $258 per km." They also reported that chick production on managed roadsides was higher than on any other cover type during 3 of 4 years of an Illinois study. Most Illinois farmers were receptive to managed roadsides (Warner and Joselyn 1978).

Managed roadsides typically are planted to an alfalfa-grass mixture (Joselyn et al. 1968). This mixture likely would be acceptable in the Texas Panhandle. Stands of alfalfa already have colonized some roadsides in the region.

A high frequency of spring sandstorms in the Texas Panhandle makes establishment of roadside habitat less feasible than in other areas. Blowing sand collects in roadside ditches, which must be cleaned periodically to allow road surfaces to drain. Roadside vegetation would accentuate the sand deposition problem. Also, some roadside ditches transport tailwater to recovery pits. Tall vegetation in the ditches would impair flow.

Dry-corner Developments

Scattered throughout the Texas Panhandle are center-pivot sprinkler systems that water about 52.8 ha. The circular system leaves four dry corners of 2.8 ha each. The dry corners usually are either disked for weed control or farmed. However, these areas offer opportunities for management of pheasant cover. The corners probably could be leased, if necessary, at relatively reasonable rates. As with management of playa lake perimeters and roadsides, vegetation that controls noxious weeds and provides pheasant cover would be required.

Travel-lane Developments

Small grains, sorghum, and corn in the northern and south-central Panhandle strata potentially supply large amounts of food to pheasants, but much of it is inaccessible because of a lack of travel lanes. Management of vegetation on county roadsides would be important for providing travel lanes for pheasants. However, additional travel lanes should be established.

No ready comprises between land use and establishment for travel lanes are apparent. Areas devoted to travel lanes will either have to be leased, or the landowner will have to have personal motives for estab-

Figure 8.—Removal of grazing will improve pheasant habitat on many playa basins.

lishing the cover. Small acreages would be required to establish a suitable network of travel lanes. If the lanes were 0.92 m wide, 4.4 km of length would occupy only 0.4 ha.

Tail-water-pit Developments

Between 40% and 50% of the tail-water recovery pits in the northern and south-central strata provide no pheasant cover (table 2) because associated vegetation is controlled rigorously (fig. 9). Since the basins cannot be farmed, they offer opportunity for pheasant habitat development. Once desirable vegetation is established, there is little or no need for control of noxious species, and less labor and fossil energy are expended. Managed tail-water pits could serve as nesting, loafing, and escape cover.

Future

Because land use in the Texas Panhandle cannot become much more intense, it would seem that the pheasant population should not be damaged by future conversions of suitable existing habitat into cropland or other uses. Declining water levels in the Ogallala Aquifer, however, bode ill for the species. This aquifer, geographically distributed approximately as the High Plains (fig. 4), is running dry because pumpage exceeds natural recharge. Projections for Castro County indicate that volume of water in the aquifer will decline over 60% by 2020 (Wyatt et al. 1976). Ground-water depletion will cause conversion of irrigated acreages to dryland farming or rangeland, which will harm pheasants. Impact of these conversions can be mitigated by stringent water conversion, but a future decline in Panhandle pheasant populations appears inevitable, notwithstanding water importation schemes.

As a preliminary step to enhance the future of Panhandle pheasants, basic research is indicated. The most pressing need is to document their life history, which is virtually unknown for this region. Such knowledge will allow us not only to optimize current use of the resource, but to suggest land uses which will have less negative impact on pheasants as irrigation decreases. Sound demographic data are needed for justifiable harvest regulations and for reliable economic models of habitat developments. Research should determine crude and specific densities, production of juveniles per unit area, survival rates of sex and age classes, harvest rates of cocks, mortality rates of hens caused by illegal shooting, and sources of nest losses. Because the Panhandle is ecologically atypical of classical pheasant range, it also is of interest to determine how pheasants have adapted to the land use and climate of this region. Knowledge of pheasant responses to cultivated habitats and to farming practices is essential to understanding population dynamics and to discovering trade-offs of mutual benefit to farmers and pheasants. As we have indicated, habitat development opportunities exist on roadsides, tail-water pits, and playa perimeters in the Panhandle. Research into the adaptability and suitability of various cover plants is in order.

Figure 9.—Tail-water recovery pits offer opportunities for development of pheasant cover.

We recognize that wildlife managers already have the technical wherewithal to make land produce pheasants. However, the economic pressures on modern farmers make it impossible to implement solid management programs. We must conclude that answers to pheasant declines lie not in routine management or research, but rather in public relations, promotion, and finance.

Perhaps the most encouraging development for the future of Panhandle pheasants is the recent incorporation of Pheasants Unlimited in Hale County, Texas. This group, which invests monies raised by raffles, auctions, and membership fees in habitat developments, may provide pheasants the economic and political boost they have sorely needed since the 1940's.

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Appendix A

Methods Used to Determine Distribution and Relative Density of Texas Panhandle Pheasants in 1977

We used a questionnaire, shown below, to determine 1977 distribution of pheasants in the Texas Panhandle. It was sent to 22 game management officers (TPWD) and 92 county extension agents in 41 counties (Yoakum, Terry, Lynn, Garza, Kent, Childress, and all counties to the north). Sixteen game management officers (73%) and 52 county extension agents (57%) responded. Twenty-five students and three faculty, Department of Range and Wildlife Management, Texas Tech University, also completed the questionnaire. Two biologists in the Panhandle provided additional data. Thus 98 individuals responded to the questionnaire.

We assumed that the number of respondents reporting occurrence in a given quarter of a county was correlated roughly with pheasant density. This number was used to establish relative density classes (high, medium, low, or none). A disproportionate concentration of respondents in Lubbock County may have caused an upward bias in relative density of this county.

Items from a questionaire used to determine distribution of ring-necked pheasants in the Texas Panhandle during 1977

Item	Question
1	Your county: ________ Name: ________ Phone: ________
2	Do ring-necked pheasants occur in your county? Yes ________ No ________
3	In which quarters of the county do pheasants occur? Southwest ______ Southeast ______ Northwest ______ Northeast ______
4	Please list other counties where you have seen pheasants in Texas.
	County ________ Quarter of County: SW ______ SE ______ NW ______ NE ______
	________ SW ______ SE ______ NW ______ NE ______
	________ SW ______ SE ______ NW ______ NE ______
	________ SW ______ SE ______ NW ______ NE ______
	________ SW ______ SE ______ NW ______ NE ______
	________ SW ______ SE ______ NW ______ NE ______
5	Did pheasants naturally colonize your county from surrounding areas? Yes ______ No ______
6	About when did pheasants naturally colonize your county? 1930 ______ 1935 ______ 1945 ______ 1950 ______ 1955 ______ 1960 ______ 1965 ______ 1970 ______ 1975 ______
7	Have any farmers, ranchers, or sportsmen released pheasants in your county? Yes ______ No ______ Don't know ______. Please give dates, locations, people involved, and ultimate success of these releases, if you can.

Appendix B

Methods Used to Quantify Land Use and Habitat Features in the Texas Panhandle

Prior to a survey of land use and habitat features during August 14-16, 1978, we divided Panhandle counties into five strata based on geographical proximity and relative density of pheasants. Six 32-km transects were established arbitrarily in each stratum. Transects were on secondary roads except when it was necessary to travel short distances on paved roads. We avoided extensive areas of rangeland. At 1.6-km intervals along each transect, we recorded crops present in the two adjacent fields and condition of both roadsides (mowed, bladed, undisturbed). These data (240 points per stratum) were used to estimate proportions of a stratum allocated to various land uses and proportions of roadsides in the specified conditions. We tallied all habitat features (travel lanes proceeding at right angles away from the transect, patches of woody cover, playas, tail-water recovery pits, drainages, idle areas, and irrigation pumps) seen along the transect. Playa basins were classified as "fenced" if they received use from livestock or "unfenced" if they did not; tail-water pits were classified as "weedy" if they provided pheasant cover or "clean" if they did not.

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Guthery, Fred S., Jay Custer, and Mike Owen. 1980. Texas Panhandle pheasants: Their history, habitat needs, habitat development opportunities, and future. USDA Forest Service General Technical Report RM-74, 11 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Pheasants (*Phasianus colchicus*) colonized the Texas Panhandle in the late 1930's. Panhandle habitat is deficient in travel lanes, secure nesting cover, and over-winter cover. The high value of cropland limits habitat development, but cover plantings may be feasible on idle areas. Aquifer depletion will probably decrease pheasant populations in the future.

Keywords: *Phasianus colchicus*, habitat, Texas

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Rocky Mountains

Southwest

Great Plains

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Insects Associated with Ponderosa Pine in Colorado

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Abstract

Ponderosa pine serves as a host for a wide variety of insects. Many of these, including all the particularly destructive ones in Colorado, are discussed in this report. Included are a key to the major insect groups, an annotated list of the major groups, a glossary, and a list of references.

Acknowledgment

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Insects Associated with Ponderosa Pine in Colorado

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Contents

INTRODUCTION

This report is about the insects associated with ponderosa pine, a major component of forests throughout the Front Range of the Rockies and also in parts of southwestern Colorado.

While many hundreds of kinds of insects can be found in the ponderosa pine forest, we are mainly interested in those that have close ecological ties with the pines—those that live in and on the trees themselves. Many of these insects are injurious to the trees and are thus particularly important to the landowner and the land manager.

Organization.—The report is divided into five sections:

1. A table listing by groups insects commonly seen in the ponderosa pine forest.
2. A key to insect-caused tree damage.
3. An annotated list of the groups and species referred to in sections 1 and 2.
4. A list of references, or sources of additional information.
5. A glossary of specialized terms.

We have kept the text as brief as possible. Readers who need help in identifying insects or recommendations on insect control should consult with specialists associated with federal, state, and local government forestry organizations. Consultation on control methods is particularly desirable, as recommended procedures are frequently updated.

General references.—There is abundant literature on the various insect groups. The book by Furniss and Carolin (1977)[4] is currently the best single reference on western forest insects and contains detailed discussions of most insect species dealt with here. Essig (1958) and Borror et al. (1976) are also good sources of general entomological information; Borror and White (1970) is a good field guide to the major groups of insects.

Insects all have scientific names, and the more important species also have common names. The common names are used where possible in this report, but where there is none, we are obliged to use the scientific name only. The following three paragraphs describe the system of scientific names and are included to help the reader better understand it.

[4]*These refer to items in Section 4—References.*

Insects are generally categorized into 26 major groups, or orders. Only 10 of these orders are commonly seen in the ponderosa pine forest (section 1). Orders are further subdivided into families, genera (singular genus), and species (singular also species). Family names always end in "-idae." Genus and species names are always italicized in print or underlined when handwritten or typed.

The genus and species, along with the author (the scientist who named the insect species), make up the scientific name. For example, the scientific name for the mountain pine beetle is *Dendroctonus ponderosae* Hopkins. Sometimes the author's name is shown in parentheses: *Dendroctonus rufipennis* (Mannerheim). This indicates that the species was originally placed in another genus. For brevity, genus names are commonly abbreviated after the first use; for example, *D. ponderosae* Hopkins. Oftentimes also the author's name is dropped after initial use.

In rare instances, an additional element is required in a scientific name to identify a subspecies. For example, the scientific name for the pine tortrix is *Choristoneura lambertiana ponderosana* Obraztsov.

Insect life stages.—All insects pass through a series of distinctive developmental stages. Most that we are concerned with pass through four life stages: egg, larva (grub, caterpillar, maggot, etc.), pupa or resting stage, and adult. Others have an abbreviated pattern of egg, nymph (resembles adult but lacks wings), and adult.

Use of this report.—Many readers will use this report to find out what kinds of insects are damaging their trees. The best way to do this, once the insects have been found, is as follows:

1. Locate the proper part of the key (section 2) for your symptoms.
2. Use the key to tentatively identify the kind of insect.
3. Look up the insect in the annotated list (section 3).
4. If desired, look up extra reading material in the references (section 4).

SECTION 1

COMMON GROUPS OF INSECTS ASSOCIATED WITH PONDEROSA PINE IN COLORADO[1]

Common names	Order	Main habitats
Grasshoppers and others	Orthoptera	On ground and foliage
Termites	Isoptera[2]	In decaying wood
Earwigs	Dermaptera[2]	In litter, under bark
True bugs	Hemiptera	On foliage, cones
Aphids, scales and others	Homoptera	On foliage
Lacewings and snakeflies	Neuroptera[2]	On foliage, branches
Beetles and weevils	Coleoptera	In or on foliage, cones or branches in cambium area or in wood
Moths and butterflies	Lepidoptera	Larvae in or on foliage, shoots, cones, or cambium area
Flies and midges	Diptera	Larvae in foliage, shoots, or cones
Ants, bees, sawflies, and others	Hymenoptera	Larvae on foliage or wood; adults on or around trees

[1]Groups of insects (e.g., dragonflies) found in the forest but not particularly associated with the trees are excluded.

[2]Orders that do not include species commonly destructive to living trees.

SECTION 2

KEY TO INSECT-CAUSED TREE DAMAGE

Index

Damage to Cones

1. Entire cones distorted and/or discolored; may be pitchy; interior portions mined or otherwise damaged	
.... cone moths	30
.... cone beetles	27
.... cone weevils	15
2. Cone scales and/or seeds stuck together; small maggots without distinctive head regions .... cone midges	34
3. Seeds hollowed out or inside material shrunken; cones appear normal	
.... seed chalcids	36
.... cone bug	8
4. Larvae and/or pupae in pith; larvae bore into seeds	
.... seed moths	32

Damage to Shoots, Twigs, or Terminals

1. Terminals only affected. No fading, needles more or less shortened, not distorted, pith mined out, terminal thickened, terminal may continue to live although superseded by lateral(s) .... shoot borer *Eucosma*	32
2. Terminals and/or laterals affected	
a. Needles faded	
(1) Shoots partly mined out	
.... pitch midges *Cecidomyia*	34
.... twig weevils *Magdalis*	15
(2) Shoots completely mined out; wood destroyed ..	
.... tip moths *Rhyacionia*	30

Page

Damage to Foliage (Needles) Only

Pag

Damage to Trunk, Entire Tree, or Wood

1. Pink or reddish frass in bark crevices and around base of tree, pitch tubes may be present, galleries in cambial area, entire tree eventually fades .... bark beetles 20
2. White frass in bark crevices in basal 0.5 m of tree, no pitch tubes, fungus-stained galleries penetrate directly into wood; usually associated with successful bark beetle attack; also in lumber .... ambrosia beetles 27
3. Large (up to golf ball size) masses of pitch on trunk (sometimes also on larger limbs) .... pitch moths 30
4. Large larvae, pupae or adults in cambial area or in wood; found in dead trees, logs, or lumber; tunnels in wood, lumber
   a. Tunnels more or less flattened or oval in cross-section
      .... roundheaded borers 12
      .... flatheaded borers 12
   b. Tunnels circular in cross-section ....
      .... horntails 36

SECTION 3

ANNOTATED LIST OF COMMON INSECT SPECIES AND GROUPS ASSOCIATED WITH PONDEROSA PINE IN COLORADO

Grasshoppers, Crickets, and Others—Order Orthoptera

Grasshoppers are known for great changes in numbers from one year to another. During outbreaks, feeding damage to a wide variety of plants is possible, including defoliation of young ponderosa pines.

Termites—Order Isoptera

Termites are soft-bodied, fragile insects that usually shun light and are secretive in their habits. They feed on nonliving wood and cause serious damage to structures in many parts of the country. In the forest they help speed decay and decomposition of dead wood. Colorado's climate is too cold for most termites, but two "subterranean" species—*Reticulitermes tibialis* Banks and *R. flavipes* (Kollar)—are known from the state. *R. flavipes* is rare. In the forest in Colorado, termites are usually found in logs or stumps, never in living parts of trees.

Earwigs—Order Dermaptera

Earwigs are scavengers on decaying plant and animal matter. Although sometimes found beneath the bark of dead or dying pines, they do no harm to trees. A large pincer-like structure at the end of the abdomen helps identify this group.

True Bugs—Order Hemiptera

Many bugs are plant feeders (also many species are predators on other insects) and are readily seen and collected as they rest on ponderosa pine foliage and branches. They are generally good fliers and have mouthparts adapted for piercing and

sucking. A few species are closely associated with the trees; many others feed on grass, herbs, and other vegetation.

Leaf-footed Bugs—Family Coreidae

One species of leaf-footed bug, *Leptoglossus occidentalis* Heidemann (fig. 1), is a large (about 15 mm long), conspicuous insect that feeds on the cones of several different conifers, including ponderosa pine. The beak is inserted through the cone scales into individual seeds, and the material within is dissolved and sucked up. A damaged seed is not readily distinguishable from a sound one; however, it will not produce a normal seedling. Under field conditions, it is doubtful that *L. occidentalis* causes enough damage to inhibit regeneration.

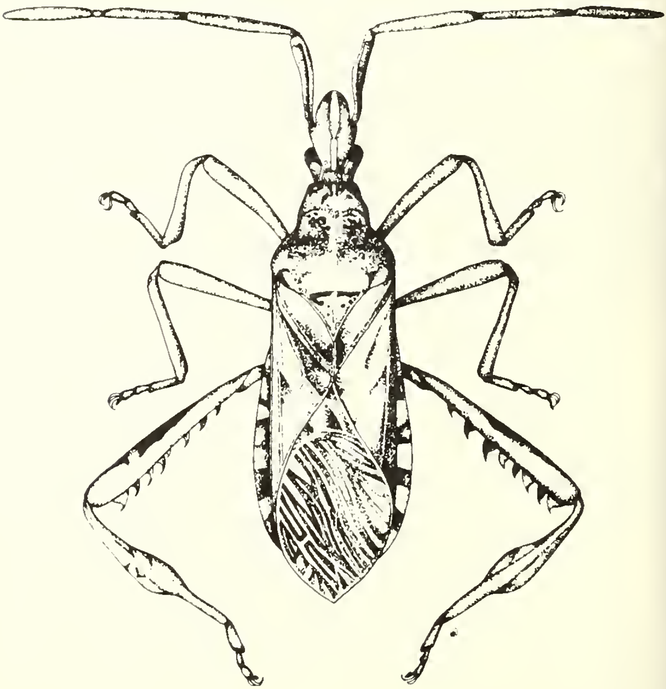


Figure 1.—*Leptoglossus occidentalis*, a seed-eating bug. Bug is about 15 mm long.

Plant Bugs—Family Miridae

Plant bugs and other small bugs are common on pine foliage and are readily collected by beating. Mirids are small (2-9 mm), fragile, and usually inconspicuous. Most are plant feeders, although none is known to feed on conifers. Members of one genus, *Neoborella*, feed on pine dwarf mistletoe.

Aphids, Scales, and Others—Order Homoptera

Members of the Homoptera are similar to the Hemiptera in that they have four wings (at least during some developmental stage) and sucking mouthparts. Many species of these insects infest Colorado ponderosa pine. The pine needle scale, *Chionaspis pinifoliae* (Fitch), is a common species, and the Prescott scale, *Matsucoccus vexillorum* Morrison, is occasionally a pest in southwestern Colorado (fig. 2). Woolly aphids, genus *Pineus*, are common on succulent new shoots in early summer. Palmer (1952) provides keys and descriptions of Colorado aphids. Other genera reported include *Cinara, Essigella, Eulachnus,* and *Schizolachnus.*

Cicadas are a group of large Homoptera that are common in the pine forest, although the adults usually do no more than rest in pine trees. Cicada nymphs (17-year locusts, etc.) live from several to many years in the soil, feeding on roots. Adults lay eggs in branches and shoots of many kinds of trees and shrubs, sometimes causing considerable shoot breakage.

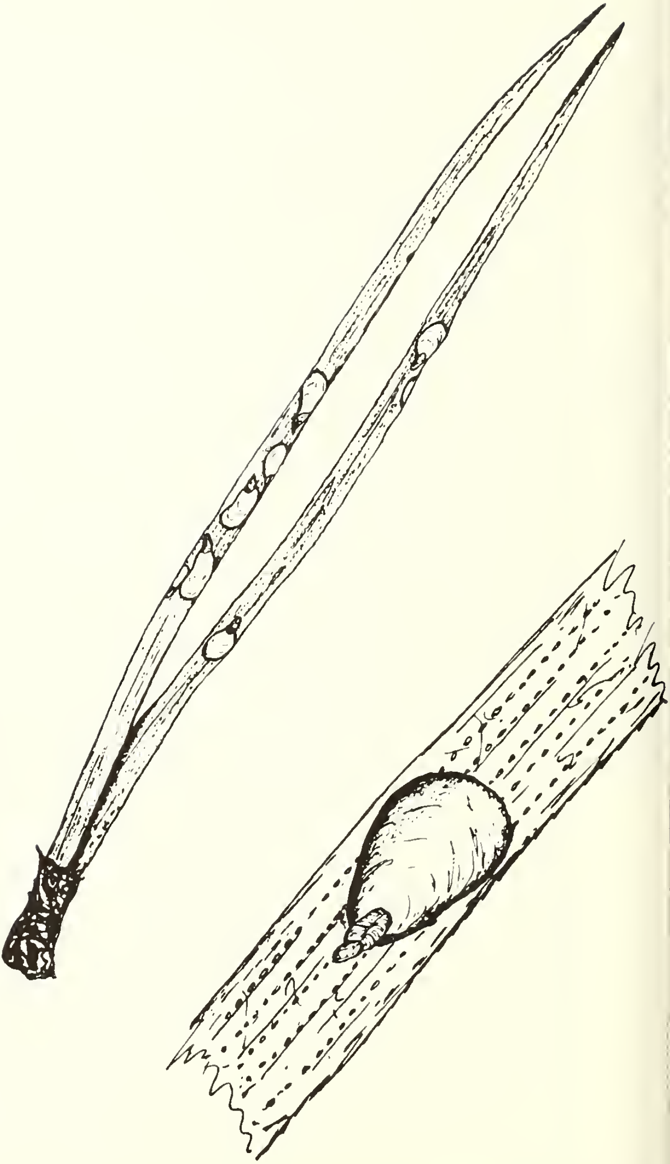


Figure 2.—Pine needle scales, 2 to 2.5 mm long.

Many members of this order are predators of pest insects in both immature and adult stages and are considered beneficial. Lacewings (fig. 3a) are light green or brown. Adult snakeflies (fig. 3b), as their name indicates, resemble serpents. Both groups have large but delicate wings. Aphids and butterfly or moth larvae are common prey.

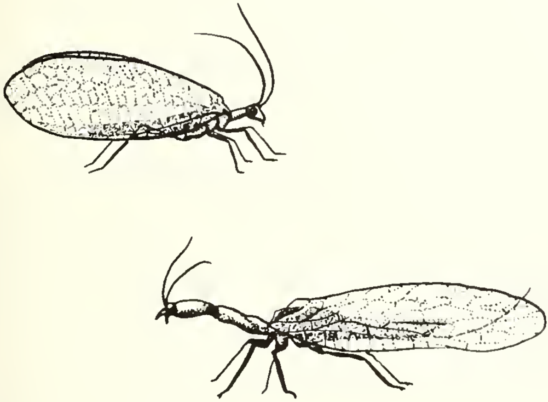


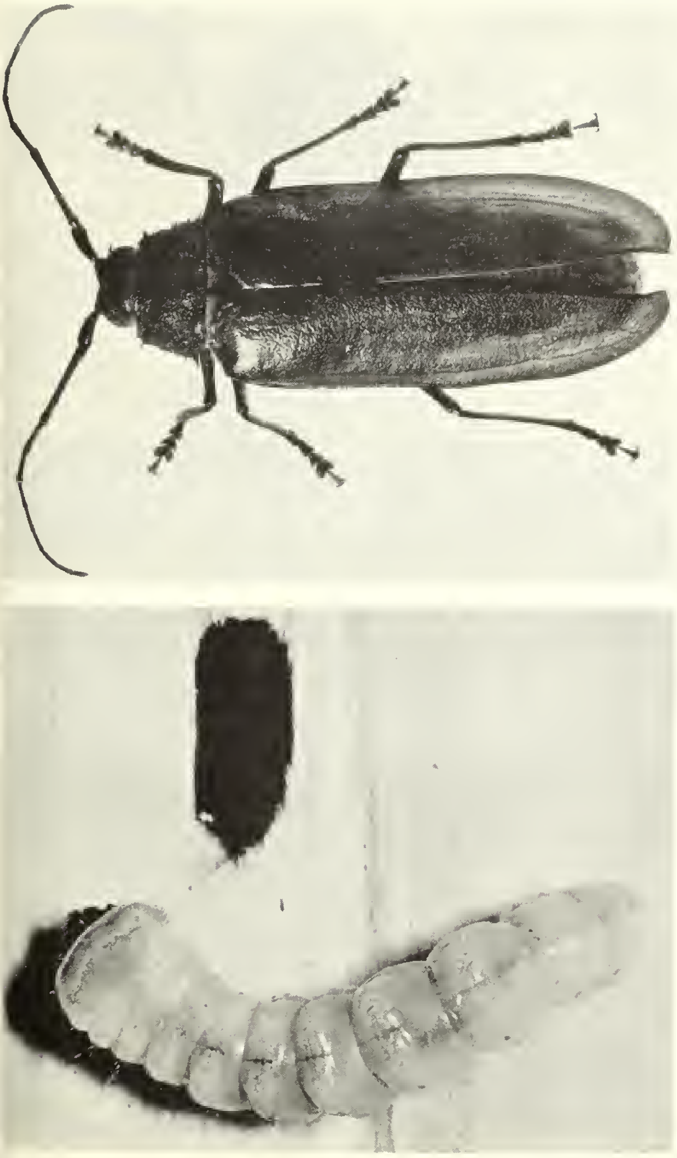
Figure 3.—Adults of (a) lacewing and (b) snakefly.

Beetles and Weevils—Order Coleoptera

Beetles are possibly the most numerous and most destructive group of insects associated with ponderosa pine. The bark beetles, family Scolytidae, are important tree-killers. Larvae of longhorned and flatheaded borers, families Cerambycidae and Buprestidae, commonly colonize recently killed trees, feeding in the cambial area and often later tunneling into the wood. Larvae of weevils, family Curculionidae, infest cones and root collars of dying trees, and adults often feed on pine foliage.

Flatheaded Borers, Metallic Wood Borers—Family Buprestidae
Longhorned Beetles, Roundheaded Wood Borers, Sawyers—Family Cerambycidae

Insects belonging to these two families (figs. 4 and 5) have similar ecological roles with respect to ponderosa pine, and tree-infesting species have similar life cycles and habits. Adult females of both families lay eggs in niches in the bark of dying or recently killed trees. Larvae tunnel in the cambial area and may subsequently move into the wood. Larval galleries make irregular patterns and become larger as the insects grow. Buprestid larvae have a typical "horseshoe nail" shape; cerambycid larvae are less flattened. Life cycles may extend over several years. Buprestids and cerambycids are often responsible for chewing noises heard coming from infested pine firewood. Borer adults occasionally emerge in houses from studs sawed from fire-killed timber that was infested while still in the woods, or from logs used in rustic cabins. Larval galleries are packed with frass and wood shavings; emergence tunnels and holes in the bark through which the adults exit the tree are open, round or oval in cross-section, and up to 5 mm in diameter. Important genera of these two families include *Monochamus, Canonura (=Acanthocinus), Ergates, Asemum,* and *Tragosoma* (Cerambycidae); and *Chalcophora, Dicerca, Buprestis,* and *Melanophila* (Buprestidae).



a

b

Figure 4.—Longhorned beetle (a) adult, 55 mm long; and (b) larva, 60 mm long, removed from feeding tunnel in wood.

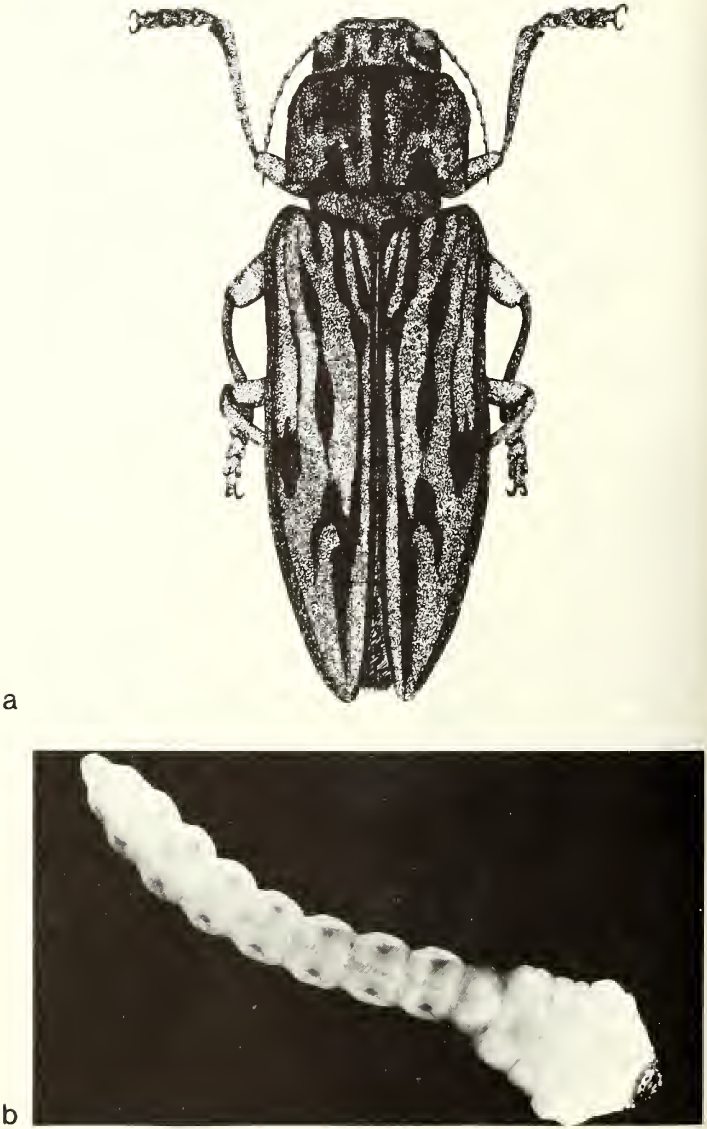


Figure 5.—Metallic wood borer (a) adult, 20 mm long, and (b) horse-shoe-nail-shaped larva, 25 mm long.

Weevils—Family Curculionidae

Weevils, or "snout beetles" (some actually have very short "snouts"), are a large and highly variable group of beetles with an equally wide variety of habits. Many species are found in and on trees, but only four genera are important to us here:

Scythropus.—Weevils of this genus are often responsible for "saw-tooth" feeding seen on pine needles (fig. 6).

Pissodes schwarzi **Hopkins (fig. 7).**—Found in rare instances infesting the root-collar area of small (>2 m tall) trees. As a general rule *P. schwarzi* is not successful in attacking healthy trees, but succeeds only in hosts weakened by some other factor.

Figure 6.—Pine needles fed on by *Scythropus* beetles.

a

b

Figure 7.—*Pissodes* (a) larva, 4.5 mm long; and (b) "chip coccoons."

Conotrachelus neomexicanus **Fall.**—This weevil, known as the "ponderosa pine cone weevil," (fig. 8) has recently been identified as a cone pest. Larvae mine indiscriminately within the cone, reducing its interior to fine sawdust-like frass. Larvae drop to the ground in midsummer, pupate in cells in the soil, emerge in fall to feed on needles and shoots, and overwinter in the adult stage.

Magdalis.—Weevils of this genus develop in twigs and branches. The adults, often colored black, bright metallic blue, or green, are commonly found on ponderosa pine foliage.

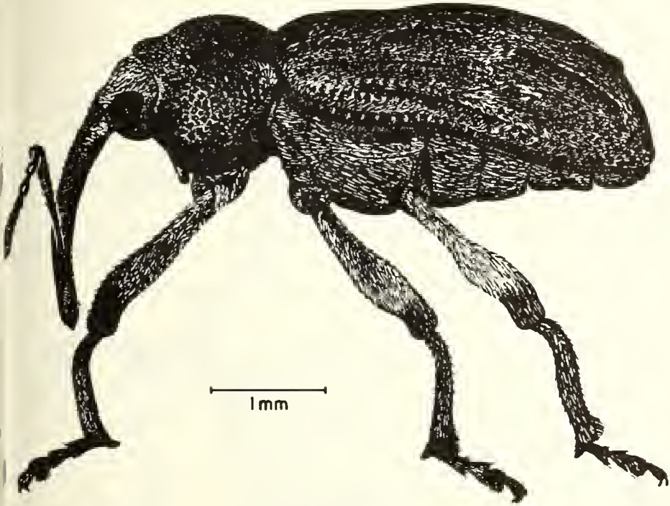


Figure 8.—Adult ponderosa pine cone weevil.

Checkered Beetles or Clerids—Family Cleridae

Several species of clerids (fig. 9) are important bark beetle predators in Colorado. Clerid larvae operate in the bark beetles' galleries and adults capture bark beetle adults on the bark surface. Following are the most important species:

Enoclerus sphegeus (Fabricius)—red-bellied clerid
E. lecontei (Wolcott)—black-bellied clerid
Thanasimus dubius Fabricius
T. undatulus (Say)

Darkling Beetles—Family Tenebrionidae

Beetles of this family, highly varied in appearance, are commonly found under the bark in decaying wood of trees killed by bark beetles. Tenebrionids are mostly scavengers. The ones seen most often are small, slender, shiny, dark-red-colored beetles.

Trogositid Beetles—Family Trogositidae (=Ostomidae)

Temnochila chlorodia (Mannerheim), a metallic bluish-green trogositid beetle, is a common bark beetle predator in Colorado.

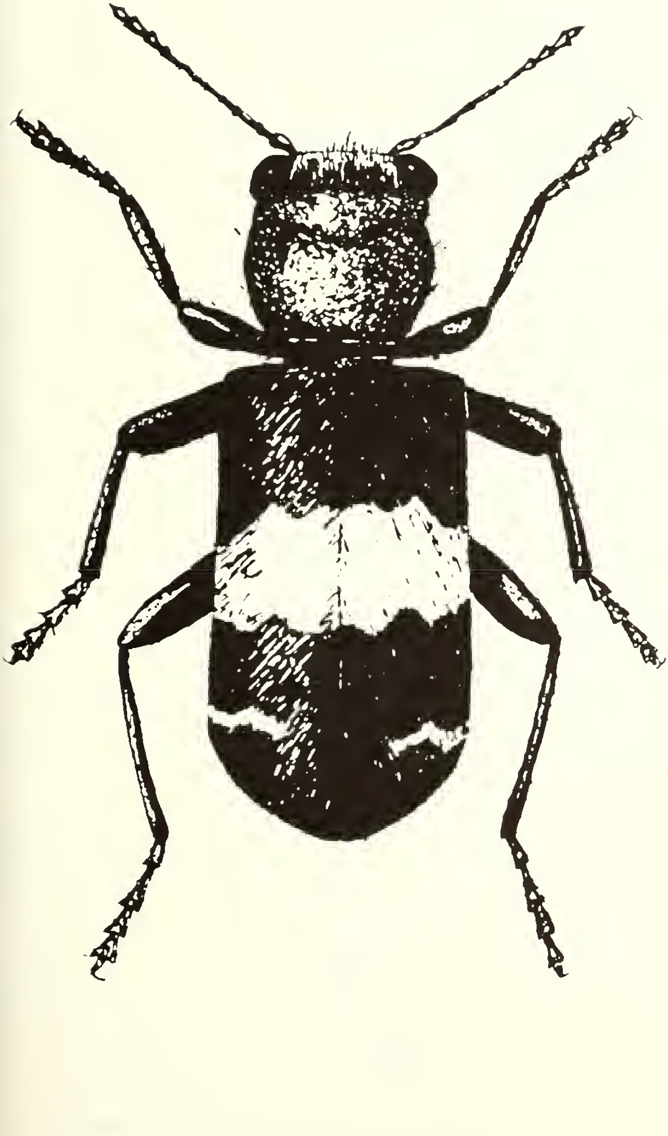


Figure 9.—Adult clerid beetle, about 10 mm long.

Bark Beetles—Family Scolytidae

Bark beetles, especially those in the genus *Dendroctonus*, are one of the most destructive groups of forest insects in western North America. Most Colorado species infesting ponderosa pine have 1-year life cycles, spending all but the summer dispersal period within the host tree. Adults of most genera bore through the bark to lay eggs in galleries (fig. 10) in the cambial area. Larvae generally mine in the same area. Their feeding galleries, in addition to the egg galleries made by the adults, create a lasting pattern of "tracks" by which the species can be identified even long after the insects themselves have disappeared.

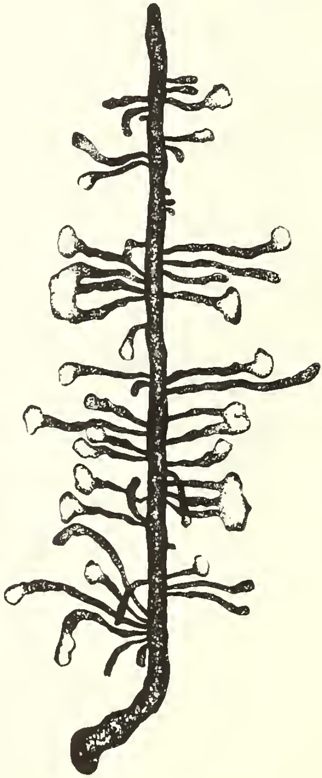


Figure 10.—Mountain pine beetle gallery system; entrance hole at bottom, vertical egg gallery, and horizontal larval galleries.

Dendroctonus ponderosae **Hopkins, mountain pine beetle (fig. 11).**— This is the most serious insect enemy of Colorado ponderosa pine. During outbreaks, it has destroyed thousands of healthy appearing trees annually. In late summer (August, generally), adult beetles bore through the bark and into the cambium area of living trees, mate, and then lay eggs in vertically oriented egg galleries. The eggs (fig. 11a) hatch in a few days and the tiny larvae (fig. 11b) begin feeding outward from the egg gallery, still in the region of the cambium. Pupae (fig. 11c) and adults (fig. 11d), develop at the ends of the larval galleries. Flight and egg laying occur generally during late July and August. Bluestain fungi introduced into infested trees by the adult beetles effectively block the trees' water and nutrient conducting system. Successfully attacked trees, although remaining green until the following summer, are in fact killed within just a few days. The beetle progeny mostly overwinter as small larvae, completing their development and emerging from their host trees to renew the cycle the following summer.

Efforts to minimize tree losses caused by bark beetles include killing beetles in infested trees before they are able to emerge to attack green living trees, spraying of individual living high-value trees to prevent beetle attack, and thinning to change conditions in forests that are susceptible to beetle outbreaks.

D. brevicomis **Le Conte, western pine beetle.**—This species is rare in Colorado ponderosa pine and is apparently restricted to the southwestern part of the state. Western pine beetle has meandering egg galleries, as opposed to the vertically oriented ones of *D. ponderosae.* The larvae, instead of remaining in the cambial area, do most of their mining in the inner and outer bark.

D. adjunctus **Hopkins, roundheaded pine beetle.**—This species is also restricted in Colorado to the southwestern part of the state and is not common.

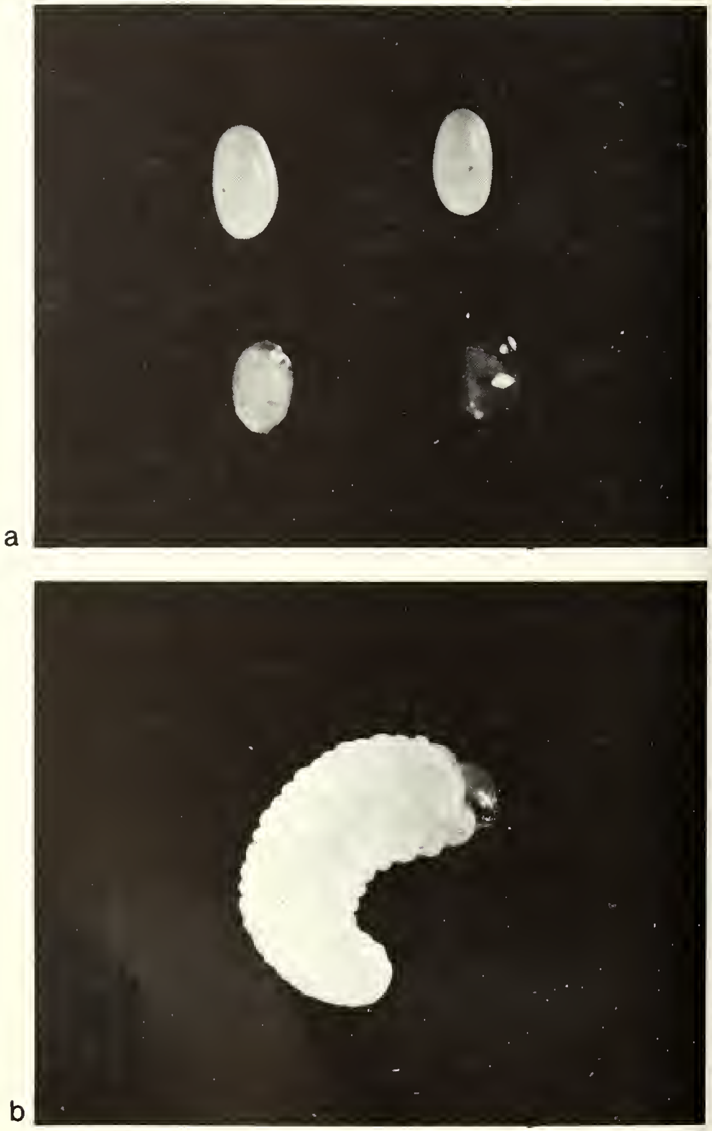


Figure 11a.—Bark beetle eggs, 0.9 mm long; 11b.—Bark beetle larva, 5 mm long.

c

d

Figure 11c.—Bark beetle pupa, 5 mm long; 11d.—Bark beetle adult, 4.5 mm long.

***D. valens* LeConte, red turpentine beetle.**—This beetle is sometimes found in the basal (up to about 0.5 m) portion of damaged trees or trees infested with other *Dendroctonus* species (fig. 12).

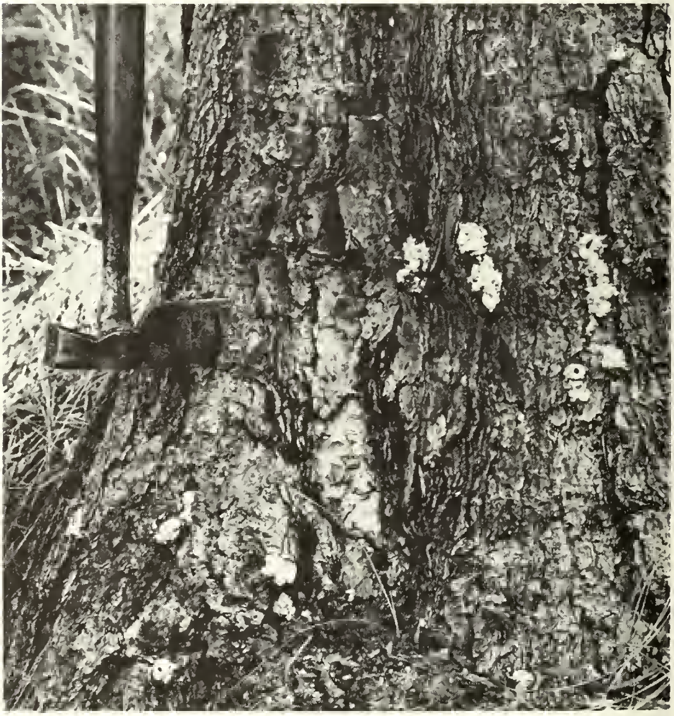


Figure 12.—Pitch tubes at base of tree resulting from attack of red turpentine beetle.

Ips **spp., ips bark beetles; pine engraver beetles.**—Ips beetles (fig. 13) are common associates of *Dendroctonus*. Their name is unusual in that it is both a common and a scientific name. Ips are generally secondary here in Colorado; that is, they are not usually tree-killers, but attack following more primary species. They commonly infest slash, creating numerous piles of frass in bark crevices. Also, fire-scorched trees are often susceptible to ips attacks and may, like slash, trigger short-lived outbreaks in standing healthy trees. *Ips* egg galleries (fig. 13b) are readily distinguished from those of *Dendroctonus*, as they are kept free of frass. Adult beetles (fig. 13a) are also easily separated from *Dendroctonus* by their concave posterior "declivity." Colorado species in ponderosa pine include:

Ips calligraphus (Germar)
I. integer (Eichoff)
I. knausi Swaine
I. pini (Say)

Hylurgops **spp.**—Adults strongly resemble *Dendroctonus*, but have noticeably rougher, less shiny bodes, and are substantially smaller. *H. subcostulatus* (Mannerheim) is known from Colorado ponderosa pine. It is also secondary (i.e., not a tree-killer) and is typically found in the basal portions of trees killed by *Dendroctonus*. Early spring-emerging *Hylurgops* beetles are often mistaken for mountain pine beetles.

Twig beetles.—Several genera of small (about 2 mm long) bark beetles sometimes infest ponderosa pine twigs and branches, causing them to flag (i.e., fade). This results in some of the natural pruning that goes on continually in the forest. Usually the infestation proceeds at low level and is inconspicuous; but, at times, high beetle populations develop, and the fading attracts attention. On rare occasions, trunks of small ponderosa pine saplings that are growing poorly can be invaded. Genera involved include *Pityophthorus*, *Pityogenes*, and *Carphoborus*.

a

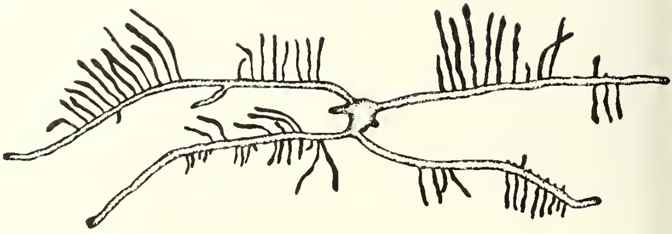


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Figure 13.—Ips beetles (a) concave spined declivity of adult, and (b) gallery system as in a down log. Note central "nuptial chamber" and radiating egg galleries. In a standing tree, gallery is oriented vertically.

Ambrosia beetles.—Ambrosia beetles are a group of bark beetles that bore directly through the bark into the wood, generally in dead or dying trees. Often they follow closely after *Dendroctonus* beetles, colonizing the basal portion of trees killed by the mountain pine beetle, attacking the following summer. The feeding habit of ambrosia beetles is different from other scolytid beetles; the larvae develop in short galleries, or "cradles," (fig. 14) prepared by the adults well within the sapwood. They feed on fungi that colonize the walls of the "cradles." The pinholes and associated stain caused by ambrosia beetles can result in downgrading of otherwise good quality lumber. Two species, *Gnathotrichus retusus* (LeConte) and *G. sulcatus* (LeConte), are common in Colorado ponderosa pine.

Conophthorus ponderosae **Hopkins, ponderosa pine cone beetle.**—This is a small bark beetle that infests ponderosa pine cones throughout the West. Adults attack the stem of the cone, and the larval galleries, made within the cone itself, result in its destruction.

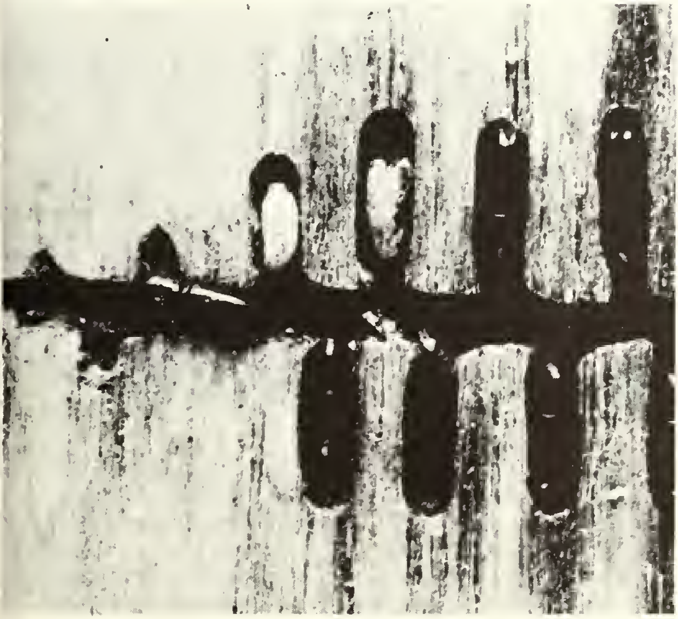

Figure 14.—Ambrosia beetles in "cradles" in wood.

Moths and Butterflies—Order Lepidoptera

Many species of moths and butterflies are closely associated with conifers, and some are destructive pests in the larval or caterpillar stage. The more important groups that feed on Colorado ponderosa pine are as follows:

Whites and Sulphurs—Family Pieridae

This family includes a number of destructive agricultural pests. One species, the pine butterfly, *Neophasia menapia* (Felder and Felder), is common throughout western ponderosa pine forests. The medium-sized, mostly white adults are often seen in the summer flitting about the tree tops. The larvae, less commonly seen, are green with white stripes, not hairy or fuzzy, and create no silken webbing as they feed on the foliage. Populations usually are maintained at low levels, but can increase to outbreak proportions and cause considerable damage.

Giant Silkworm Moths—Family Saturniidae

The genus *Coloradia* contains two species, *C. pandora* Blake, and *C. doris* Barnes, known to injure Colorado ponderosa pine. Larvae of both these so-called pandora moths feed on old needles, gregariously at first and individually when mature. Full-grown larvae are large, up to 80 mm long, and usually light yellow-green or gray-green. They have a white stripe running down the center of the back and short, stout black spines on each body segment. Pupation is in the soil under infested trees. The thick-bodies adults are dark gray with yellow antennae and often bright pink hairs on the hind wing bases and interior margins. Depending on species, the life cycle requires 1 or 2 years.

Tiger Moths—Family Arctiidae

Larvae of several species of tiger moths (genus *Halisidota*) build heavy webs (fig. 15) in terminals (and occasionally laterals) on pines and other western conifers. From these webs, the larvae move out to feed on the foliage. Little damage appears to result, but the webs are conspicuous and often attract attention. *H. ingens* Hy. Edwards, probably the main Colorado species, overwinters in the larval stage and can be found feeding on warm winter days.

Figure 15.—*Halisidota* web and defoliation caused by feeding larvae.

Pyralid Moths—Family Pyralidae

Several species of the genus *Dioryctria* infest different parts of ponderosa pine (fig. 16). *D. cambiicola* (Dyar) is among the most common. Larvae of this species work mainly in branch tips, killing the outer several centimeters and producing a conspicuous mass of pitch and frass on the outside of the twig. This mass distinguishes the work of *D. cambiicola* from that of *Rhyacionia* (tip moth) larvae (Lepidoptera:Tortricidae) which also kill branch and leader tips, but do not stimulate the tree to produce pitch. Infestations of *Dioryctria* are rarely if ever heavy enough to be serious. *D. rossi* Munroe, *D. auranticella* (Grote), and *D. abietivorella* (Grote) are known to infest ponderosa pine cones in Colorado. Pine webworms, genus *Tetralopha*, have recently been reared from ponderosa pines in the vicinity of Fort Collins, Colo.

Figure 16.—Adult *Dioryctria* moth, wing span about 25 mm.

Leafroller Moths—Family Tortricidae

Four genera of tortricid moths are commonly found infesting Colorado ponderosa pines. Among them are several potentially serious pests of regeneration, stands being managed for high-value forest products, and/or high value individual trees growing as ornamentals in urban situations.

Rhyacionia **spp.**—Several species of *Rhyacionia* pine tip moths are known from Colorado ponderosa pine. These include the southwestern pine tip moth, *R. neomexicana* (Dyar), the western pine tip moth, *R. bushnelli* Busck, and *R. fumosana* Powell. All the pine tip moths infest new shoots, hollowing them out. Severe tree stunting is possible, but mortality is rare. *R. neomexicana* is a serious pest of pines planted for landscaping purposes along the Front Range and can also be important in windbreak and Christmas tree plantings. Fortunately, once trees grow beyond 3 to 4 m tall, they are no longer attacked severely. On smaller trees, though, damage can be so serious that chemical control measures may be required.

***Petrova*.**—One species, *P. metallica* (Busck), is known from Colorado. These "pitch nodule moths" mine in new shoots and produce a consolidated mass of pitch at the site of entry into the shoot, like *Dioryctria cambiicola*. As in the case of *D. cambiicola*, the portion of the shoot beyond the pitch nodule dies, and stunting and deformation result.

***Eucosma*.**—Larvae of the western pine-shoot borer, *E. sonomana* Kearfott, are responsible for reduced height growth of ponderosa pine in certain Colorado locations. The larvae infest new terminals, but feed only in the pith; the terminal often lives, but is stunted. Laterals assume dominance; or the leader retains dominance, but is short. A characteristic "shaving brush" appearance results as shoot length is reduced and needle bundles are more closely spaced than usual. After a short feeding period, the larvae abandon the aerial portion of the tree to overwinter in silken cocoons in the soil.

***Cydia (= Laspeyresia)*.**—This genus includes several species of "seed moths" reported from Colorado. Distribution and relative abundance of the insects are unknown, as is their impact on ponderosa pine seed production.

Pine tortrix, ***Choristoneura lambertiana ponderosana*** **Obraztsov.**—They are common in certain ponderosa pine areas in some years. Heavy defoliation has tended to be localized in canyons and along highways, rather than being extensive, and the tortrix is not considered a major pest. Larvae feed on new needles and can cause total loss of the current year's foliage. They chew through the needle sheath and feed on the succulent new needle tissue inside. Abundant unconsolidated webbing is produced. Damaged needles fade rapidly and drop by winter. The insects pupate in the tips near the feeding sites. Eggs are laid in overlapping rows on the older needles, and the tiny larvae overwinter in silken hibernacula in protected locations on the tree.

Gelechiid Moths—Family Gelechiidae

This family includes a group of moths known as needle miners (fig. 17). Larvae mine out the inside of needles, leaving them hollow. One species, *Coleotechnites ponderosana* Hodges and Stevens, has recently been recognized as a pest in the Front Range as well as in the Black Forest and Durango areas.

Figure 17.—Needle miner larvae inside ponderosa pine needles.

Ermine Moths—Family Yponomeutidae

One species of ermine moth, *Zelleria haimbachi* Busck, is known from Colorado ponderosa pine. *Z. haimbachi,* the pine needle sheath miner, feeds in the latter larval stages much like the pine tortrix, and defoliation caused by the two is superficially hard to separate. Both pupate in masses of silk in the mined shoots; however, *Z. haimbachi* larvae overwinter within pine needles while those of the pine tortrix overwinter within hibernacula in bark crevices.

Flies and Midges—Order Diptera

A few species of flies and midges damage Colorado trees. In ponderosa pine, these are mainly from two families of gall midges—Cecidomyiidae and Itonididae. *Contarinia coloradensis* Felt (Cecidomyiidae) causes excessive tissue growth of needles within the fascicle; galls (fig. 18) so formed are globular and 6 to 12 mm in diameter. Galled needles are short and drop prematurely; severe defoliation can result. Heavy infestations seem to be localized.

Cone midges are reported from Colorado ponderosa pine cones, but little is known about them. The larvae of these insects are tiny (3 mm), red, pink, or orange maggots found within and around cone scales and seeds. Adults are tiny, fragile, inconspicuous flies. *Rubsaamenia keeni* Foote is an example of one of these.

Larvae of pine resin midges, similar in appearance to the cone midges, occasionally colonize ponderosa pine shoots and cause flagging much like that resulting from work of tip moths, twig beetles, and the like. The gouty pitch midge, *Cecidomyia piniinopsis* Osten Sacken, is a widely distributed species known from Colorado ponderosa pine.

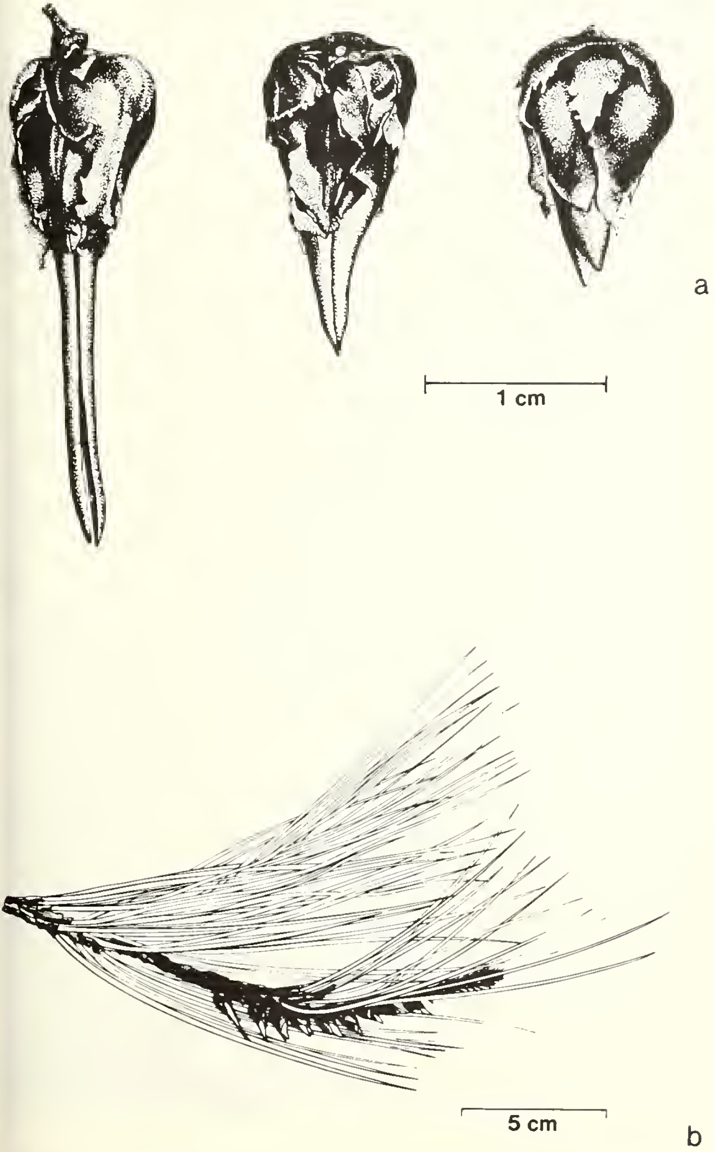

Figure 18.—Galls in ponderosa pine due to infestation by gall midges (a) shows variability; (b) shows galls in place on shoot.

Ants, Bees, Sawflies, and Allies—Order Hymenoptera

Members of the Hymenoptera are not usually serious forest pests in Colorado. Sawflies, family Diprionidae, are the most common; *Neodiprion fulviceps* (Cresson), *N. gilletti* (Rohwer), and *Zadiprion townsendi* (Cockerell) are among the species found. The name ''sawfly'' refers to the saw-like ovipositor with which females make the slits in pine needles where they deposit their eggs. Larvae (fig. 19) of these sawflies feed on the foliage and drop to the soil to pupate. Like many other defoliators, they may also feed on the exterior surfaces of young tender shoots. Young sawfly larvae feed in clusters on individual needles. No webbing is produced. The larvae have shiny (often black) heads and a distinctive habit of rearing back from their feeding position when disturbed. Each species overwinters in one of three life stages: egg, larva, or pupa. *Z. townsendi* overwinters in the larval stage.

Figure 19.—Young sawfly larvae, about 12 mm long, clustered characteristically on pine needles.

Horntail Wasps—Family Siricidae

Larvae occupy ecological niches similar to those of the wood-boring beetles. Larvae tunnel in the sapwood of recently killed trees, including ones killed by forest fires. *Sirex, Xeris,* and *Urocerus* are common genera in Colorado. The name "horntail" refers to the dangerous-looking ovipositor on the adult female and also to a posterior projection on the larvae.

Ants—Family Formicidae

Ants are commonly found in and around pine trees. They have no direct effect on living trees, but presence of ants often indicates the presence of aphids, from which the ants obtain honeydew. In some cases, protection afforded aphids by ants may favor aphid population increases. Several species of ants commonly obtain nectar from ponderosa pine dwarf mistletoe, and in the process pollinate dwarf mistletoe flowers. Carpenter ants, large black species, often tunnel extensively in down and decaying wood and sometimes colonize unfinished wood in cabins and other structures.

Braconids, Chalcids, and Ichneumons—Families Braconidae, Chalcididae, and Ichneumonidae

Many insect species in these families are parasites of other—often harmful—insects. One genus of chalcids, *Megastigmus*, includes several species that colonize conifer seeds and can be pests. *M. albifrons* Walker may occur in Colorado.

SECTION 4

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SECTION 5

GLOSSARY

Antennae (sing. antenna): The pair of jointed appendages on the insect head, commonly called feelers.

Beak: The protruding mouthparts of certain kinds of insects (e.g., aphids and cicadas) through which the insect feeds.

Beating: A method of collecting insects in which foliage or branches are beaten over a cloth onto which the insects drop.

Blue stain: Discoloration in wood caused by fungi, usually genus *Ceratocystis,* which are carried by bark beetles.

Cambium: In a tree, the growing part between the inner bark and the wood.

Cambial: Pertaining to the area of the cambium.

Chalcid: A small (1- to 3-mm long), heavy-bodied wasp belonging to the family Chalcididae.

Cone: The female reproductive structure of a conifer; the part that bears the seeds.

Cone scales: The woody (in pines) individual elements of a cone attached to the central core.

Conifer: A member of the group of cone-bearing trees; generally have needles.

Crown: The part of the tree having branches and foliage; the upper part.

Declivity: In bark beetles, the sloping upper rear portion of the abdomen.

Defoliator: An insect that chews foliage from trees.

Dominance: In conifers, the tendency of the topmost shoot to remain the tallest as the tree grows.

Dwarf mistletoe: A fleshy parasitic plant that grows on conifers.

Fading: Yellowing or similar discoloration of foliage, often resulting from insect activity.

Fascicle: In conifers, particularly pines, an individual bundle of needles.

Flag: To fade.

Flagging: A conspicuous clump of fading foliage; dead needles, usually on the ends of branches.

Frass: The mixture of feces and sawdust left behind by many chewing insects.

Gall: An abnormal growth of plant tissues, normally stimulated by some outside factor, often insects or mites.

Gallery: A series of chambers and/or tunnels in which insects, particularly bark and ambrosia beetles, live. Each species has its particular kind of gallery, and can often be identified by it.

Habitat: The place where an insect lives.

Hibernaculum (pl. hibernacula): A tiny shelter constructed of silk or some other material in which an insect (usually a larva) overwinters or hibernates.

Honeydew: A sugary excretion produced by aphids and other sucking insects.

Host: The plant (or animal) on which an insect feeds.

Lateral: On a pine tree—a more or less horizontal limb or branch, as opposed to the leader, or topmost tip of the tree.

Maggot: Legless, worm-like fly larva (Diptera).

Midge: A small, fragile fly, often resembling a mosquito.

Mine: To bore or dig beneath the surface (e.g., the activity of certain kinds of insects). n., the hollowed-out area resulting from mining.

Needle sheath: On pines, the fibrous wrapping of the needle bundle that helps hold the bases of the needles together.

Niche: What the insect does; the role it plays in the environment.

Overwinter: In the case of insects, to pass the winter, often in an active developmental stage.

Oviposit: To lay eggs.

Ovipositor: In certain female insects, the structure with which the eggs are placed.

Pith: In twigs of trees and shrubs, the more porous, central part.

Population dynamics: How populations change in number of individuals from generation to generation.

Predator: An organism that feeds, usually externally, on another.

Regeneration: In forestry, this generally refers to young seedling or sapling trees.

Root collar: The part of the stem of a tree just below the surface of the ground.

Scale, Scale insect: One of a group of sucking insects that become fixed at feeding locations, covering themselves individually with a more or less hard protective coating.

Slash: Branches, treetops; generally parts of trees left in the woods after logging.

Stage: In insects, any of the developmental periods (e.g., larval stage).

Terminal (syn. leader): The topmost shoot of the main stem of a tree.

Stevens, Robert E., J. Wayne Brewer, and David A. Leatherman. 1980. Insects associated with ponderosa pine in Colorado. USDA Forest Service General Technical Report RM-75, 42 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Ponderosa pine serves as a host for a wide variety of insects. Many of these, including all the particularly destructive ones in Colorado, are discussed in this report. Included are a key to the major insect groups, an annotated list of the major groups, a glossary, and a list of references.

Keywords: *Pinus ponderosa, insects*

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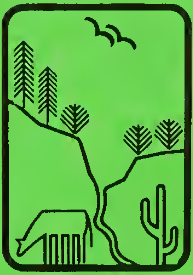

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Research programs at the Rocky Mountain Station are coordinated with area universities with other institutions. Many studies are conducted on a cooperative basis to accelerat solutions to problems involving range, water, wildlife and fish habitat, human and communi development, timber, recreation, protection, a multiresource evaluation.

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